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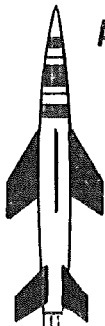
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**CALIBRATION OF THE PWT 16-FOOT  
TRANSONIC CIRCUIT WITH A MODIFIED MODEL  
SUPPORT SYSTEM AND TEST SECTION**

By

H. L. Chevalier  
PWT, ARO, Inc.

August 1960

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*-William O. Cole-*

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ARO Project No. 220103

Contract No. AF 40(600)-800 S/A 11(60-110)

## ABSTRACT

Tests were conducted in the 16-Ft Transonic Circuit of the Propulsion Wind Tunnel Facility to determine the Mach number calibration, Mach number distributions, operating limitations of the tunnel, and usable length of the test section after several modifications had been made to the tunnel. These modifications included changes in the test section bulge region, leading edge of the sting support strut, and tunnel scavenging scoop.

The modifications did not change the basic tunnel calibrations, although the region of uniform Mach number distribution at supersonic Mach numbers was extended from tunnel station 22.0 to station 24.0. The results also show that, although tunnel pressure ratio affects Mach number distributions and model base pressure in the aft portion of the test section, sting support interference is predominant aft of station 14.0.

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## NOMENCLATURE

$C_{p, b}$	Base pressure coefficient, $(p_b - p_\infty)/q_\infty$
$f_d$	Diffuser flap opening, in.
$M_\infty$	Free-stream Mach number
$p_b$	Base pressure, psf
$p_c$	Plenum chamber static pressure, psf
$p_t$	Tunnel total pressure, psf
$p_\infty$	Free-stream static pressure, psf
$q_\infty$	Free-stream dynamic pressure, psf
$W$	Weight flow through the tunnel, calculated at tunnel station 0, lb/sec
$W_p$	Weight flow through plenum chamber, measured in the ducting to the plenum compressors, lb/sec
$\theta_w$	Test section wall angle (the angle between the test section sidewall and the tunnel centerline, positive for diverged walls), deg
$\lambda$	Tunnel pressure ratio (ratio of tunnel total pressure to the static pressure at the downstream end of the diffuser)



## INTRODUCTION

Several modifications have been made to the 16-Ft Transonic Circuit of the Propulsion Wind Tunnel Facility, Arnold Engineering Development Center (PWT-AEDC) to reduce the lateral vibrations originally experienced with sting supported models. These modifications included reducing the depth of the test section bulge region, moving the entire bulge section downstream, blunting the leading edge of the support strut, and moving the tunnel scavenging scoop downstream and adding a conical nose fairing. A detailed discussion of these modifications is given in Ref. 1. This investigation was initiated to determine the Mach number calibration, Mach number distributions, operating limitations of the tunnel, and usable length of test section after the modifications were made.

The Mach number in the Transonic Circuit is established by adjusting both tunnel pressure ratio and plenum flow rate. In general, it is possible to establish a given Mach number using several combinations of tunnel pressure ratio and plenum flow rate. However, previous calibrations have shown that a particular combination of tunnel pressure ratio and plenum flow rate at each Mach number will produce the maximum length of constant Mach number flow in the test section. Reference 2 shows that total power required for operating the tunnel decreases with increasing plenum flow. Therefore, during this investigation, the relative amounts of tunnel pressure ratio and plenum flow were varied from minimum to maximum at each Mach number to determine the combination which produced a uniform flow over the greatest length of test section with the minimum total drive power.

Mach number distributions were determined for each supersonic Mach number at two test section sidewall angles, zero and optimum. The optimum wall angles corresponded to the wall angles recommended in Ref. 3 for the least amount of wall interference. Previous tests in the tunnel using the optimum wall angles had indicated that the available plenum flow rate was not sufficient to maintain Mach number in the region between Mach number 1.0 and 1.2 at the higher values of tunnel total pressure. During this investigation various diffuser flap openings were used to supplement the plenum flow rate in an effort to increase the maximum total pressure in the above Mach number region.

For the high values of tunnel pressure ratio, the flow begins to accelerate in the aft portion of the test section, and for low values of pressure ratio the pressure recovery begins in the aft portion of the test section. Although this effect is shown by test section Mach number distributions,

Refs. 4 and 5 show that model base pressure measurements are more sensitive to changes in tunnel pressure ratio; the optimum value of tunnel pressure ratio obtained with a model present is higher when determined by base pressure measurements than when determined by the Mach number distributions. Reference 4 also shows that for a pylon supported model with the sting support system removed, the base pressure was insensitive to tunnel pressure ratio at the forward test section locations and became more sensitive as the model was moved aft. Reference 5 showed similar results for a sting mounted model, although support interference became predominant over tunnel pressure ratio effects when the model was moved aft in the test section.

For the present investigation, a sting supported model similar to the one described in Ref. 5 was used. The use of this model provides for determination of both tunnel pressure ratio and support interference effects.

## APPARATUS

### TUNNEL

The PWT 16-Ft Transonic Circuit is a variable density, closed-circuit wind tunnel capable of operation at Mach numbers from 0.50 through 1.60 and at stagnation pressures up to approximately two atmospheres. The test section is 16 ft square and is lined with perforated plates to allow continuous operation through the Mach number range with a minimum of wall interference. The two test section side walls are movable to allow various wall angle settings as an additional aid in minimizing wall interference at the supersonic Mach numbers. Immediately downstream of the test section is a 20-ft length of movable diffuser, referred to as diffuser flaps. The entire width of the diffuser sidewalls and a 12-ft center section of the upper and lower diffuser walls may be diverged to approximately 18-in. to allow re-entry of air from the plenum chamber. This additional airflow may be used to supplement the plenum evacuation system. For this investigation only the upper and lower flaps were used. A sketch of the test section region and a detail of the test section wall liner is presented in Fig. 1. A more extensive description of the test facility is given in Ref. 6.

### TUNNEL MODIFICATIONS

The model support used in the 16-Ft Transonic Circuit consists of a two-dimensional strut located in a vertical position midway between the

two sidewalls. Originally the strut had a modified double wedge section which was changed by blunting the leading edge of the strut to a 3:1 elliptical section. The tunnel bulge section which originally started at tunnel station 23.7 was moved downstream to tunnel station 27.7 and was decreased in depth from 1.33 ft to 0.50 ft (see Fig. 2).

The combustion products from propulsion systems are removed from the tunnel by a scavenging scoop at the rear of the test section. Previously during aerodynamics tests, the scavenging scoop was fitted with an open bluff shape cowling and was used to remove air from the tunnel for control of humidity and pressure level. However, with the modifications, the length of the scoop was shortened from tunnel station 43.0 to 50.3, and the bluff shape cowling was replaced with a closed 40-deg cone. Air is now removed from the tunnel through flaps in the scavenging scoop support strut. Details of these modifications are shown in Fig. 2.

## TEST ARTICLES

Test section static pressure distributions were obtained using a centerline probe mounted in the sting support system. The probe had pressure orifices spaced at 6-in. intervals from tunnel station 1.5 to 24.5.

For determining the effects of tunnel pressure ratio and support interference on model base pressure, a 1.92-percent blockage cone-cylinder model was mounted on the centerline probe. This model could be moved axially along the probe to various test section locations. The base of the model was aligned with one of the probe orifices which was used to measure base pressure. Figure 3 shows details of the centerline probe and model.

## TEST PROCEDURE

The tunnel was calibrated by adjusting the pressure in the plenum chamber surrounding the test section until the desired Mach number was obtained in the test section for a given tunnel total pressure and nozzle setting. All subsonic Mach numbers were obtained with a Mach number 1.0 nozzle contour. For supersonic Mach numbers, the nozzle contour was set corresponding to the Mach number.

For the investigation of variation in Mach number distribution and base pressure with tunnel pressure ratio, the Mach number was initially set with the minimum amount of plenum flow rate and by adjusting the pressure ratio to the required value to establish the Mach number. The

pressure ratio was then decreased, and the plenum flow rate increased progressively to maintain a constant Mach number until the plenum flow rate became limited by the capabilities of the plenum compressors (approximately 23,000 cfs). For Mach numbers 1.3 and greater, the minimum tunnel pressure ratio was limited by sting support vibrations (Ref. 1).

## RESULTS

### MACH NUMBER CALIBRATION

Earlier calibrations of the Transonic Circuit have shown that the plenum chamber pressure can be used as a reference pressure to set the free-stream Mach number. The free-stream static pressure was determined by arithmetically averaging the static pressure measured on the centerline probe between tunnel station 1.5 and the end of the level portion of the distribution. The calibration is presented in Fig. 4 for both zero and optimum wall angles as the difference between the average free-stream static pressure ( $p_\infty$ ) and the plenum chamber pressure ( $p_c$ ) divided by the total pressure of the airstream ( $p_t$ ). The various optimum wall angles used are also shown in Fig. 4. The calibration is unaffected by the amount of plenum flow rate used in establishing the Mach number, as is shown in Fig. 4. The calibration shown in Fig. 4 differs only slightly from previous calibrations at zero wall angle (Ref. 2). Calibrations at optimum wall angles were not available previously.

As mentioned in the Introduction, it is possible to establish the Mach number using several combinations of tunnel pressure ratio and plenum flow rate. Figures 5 and 6 show the Mach number distributions for various values of tunnel pressure ratio between the maximum and minimum at which the Mach number could be maintained. Distributions are presented for each wall angle and Mach number. Since Mach numbers 0.50 and 0.60 have to be set without plenum flow, these data were obtained at only one particular value of pressure ratio.

Figure 5 shows that at the subsonic Mach numbers, the Mach number distributions at the rear of the test section are affected by variations in tunnel pressure ratio. At the lower pressure ratios, a deceleration of the flow at the rear of the test section causes an increase in pressure which requires large amounts of plenum flow, and at very low pressure ratios the plenum flow requirement exceeds the capacity of the plenum evacuation system. However, the deceleration only exists downstream of station 18, and with a slight increase in tunnel pressure ratio a uniform Mach number distribution can be maintained to station 22. The subsonic Mach number

distributions indicate that the region between station 1.50 and 20.0 can be used for testing without exceeding  $\pm 0.005$  in Mach number variation.

The Mach number distributions at supersonic speeds are not affected by variation in tunnel pressure ratio. For supersonic Mach numbers (Figs. 5 and 6), a flat Mach number distribution is maintained to station 24.0. The variation in Mach number is  $\pm 0.02$  over the region from station 1.5 to 24.0, although a smaller variation can be obtained with short models by proper positioning of the model in the test section.

The effect of diffuser flap opening on the Mach number distributions is shown in Fig. 7. It will be shown later that opening the flaps helps to supplement the plenum flow rate in obtaining maximum tunnel total pressure at Mach numbers of 1.05 and 1.10 at highly converged wall angles. All the distributions shown in Fig. 7 were obtained using the maximum capacity of the plenum evacuation system. Figure 7 shows that flap position has no effect on the test section Mach number distributions.

Figure 8 shows the variation of tunnel pressure ratio with plenum flow for zero and optimum wall angles.

#### MAXIMUM OPERATING CONDITIONS

Figure 9 shows the variation of maximum total pressure with Mach number. The maximum total pressure is limited by available power which includes the electrical energy required by the main drive compressor and the plenum suction compressors, except at low Mach numbers (below 1.20) where 4000 psf is the maximum resulting from structural limit of the tunnel shell.

Converging the test section sidewalls at Mach numbers between 1.00 and 1.20 results in a large reduction in maximum total pressure. The limiting values shown in Fig. 9 for Mach numbers between 1.00 and 1.20 were obtained with maximum tunnel pressure ratio, plenum flow, and diffuser flap opening.

Figure 10 shows the effect of opening diffuser flaps on the maximum obtainable total pressure for zero and converged (optimum) wall angles at Mach numbers of 1.05 and 1.10. This plot shows that opening flaps helps to increase the maximum total pressure at converged wall angles but lowers the total pressure at zero wall angle. Divergence of the test section sidewalls for Mach numbers above 1.20 had no effect on the maximum total pressure. Figure 10 also shows the recommended flap openings for Mach numbers from 1.00 to 1.20 using optimum wall angles.

## PRESSURE RATIO AND SUPPORT INTERFERENCE

Variations in base pressure coefficient with tunnel pressure ratio at three tunnel stations are shown in Fig. 11. With the model base placed at tunnel station 14.0, the results are similar to the results obtained in Refs. 4 and 5 in that the base pressure coefficient is independent of tunnel pressure ratio. Moving the model aft in the test section to tunnel station 17.5 resulted in an increase in the base pressure at all Mach numbers at the lower values of pressure ratio. For Mach numbers below 1.00, the base pressure could be decreased to the value obtained at station 14.0 by increasing the pressure ratio. For Mach numbers of 1.00 and greater, the base pressure was only slightly affected by variation in tunnel pressure ratio. With the model base at station 20 the base pressure was increased at all Mach numbers and could be decreased only at a Mach number of 0.70 to the value obtained at station 14.0.

It should be noted that the values of base pressure at tunnel station 14.0 do not correspond to test results on bodies of revolution which have larger fineness ratios. Using a 1.74-caliber length of afterbody does not allow the pressure on the body to return to free-stream static pressure before the base of the body is reached. However, this will not affect the results of this test since only relative values of base pressure are discussed.

Figure 12 shows the variation of base pressure coefficient with model base location at several values of pressure ratio. It is evident from this figure that, as the model is moved aft in the test section, the base pressure is affected by support interference being propagated upstream through the model wake, and the support interference effects are greater than the effects of tunnel pressure ratio. The centerline Mach number distributions shown in Figs. 5 and 6 indicate that the usable test section extends to tunnel stations 22 for subsonic Mach numbers, and 24.0 for supersonic Mach numbers, whereas this phase of the investigation shows that consideration must also be given to support interference for large diameter models. For the configuration used in this investigation, the limiting tunnel station, to avoid support interference, would be forward of station 14.0. For other configurations, consideration of the model base shape, size, ratio of base diameter to sting diameter, the included angle of the sting adapter, and distance to the adapter will change the limiting location of the model base. A more extensive investigation is needed to clearly define the extent of this support interference problem.

Varying tunnel pressure ratio changes the base pressure coefficient as far forward as station 14.0 for Mach numbers below 1.00 and forward to station 18.0 for supersonic Mach numbers. Although sting support interference is the predominant tunnel effect aft of station 14.0 for the model

used in this investigation, the tunnel should be operated at the values of tunnel pressure ratio for which the tunnel pressure ratio effects are minimized.

### CONCLUSIONS

The following conclusions were reached as a result of the calibration of the 16-Foot Transonic Circuit and model base pressure investigation:

1. Varying the tunnel pressure ratio with corresponding variation of plenum flow rates at a particular Mach number had no effect on tunnel calibration.
2. Varying test section sidewall angle varied the tunnel calibration.
3. At subsonic Mach numbers, the region between tunnel station 1.5 and 22.0 has a uniform Mach number distribution, and at supersonic Mach numbers this region extends to station 24.0. The variation in Mach number is  $\pm 0.005$  for the region between tunnel station 1.5 and 20.0 at subsonic Mach numbers and  $\pm 0.02$  for the region between tunnel station 1.5 and 24.0 at supersonic Mach numbers.
4. Opening diffuser flaps helps to increase the maximum tunnel total pressure for converged test section walls but decreases the maximum tunnel total pressure for zero wall angle at Mach numbers between 1.0 and 1.2.
5. Both tunnel pressure ratio and support interference affect base pressure coefficients when a 30-in. -diam cone-cylinder model is installed at the aft end of the test section. Changes in pressure ratio affect base pressure coefficient forward to tunnel station 14.0 for subsonic Mach numbers and forward to station 18.0 for supersonic Mach numbers.
6. For the model configuration used in this investigation, the limiting tunnel station to avoid support interference would be forward of station 14.0. However, a more extensive investigation is needed to clearly define the extent of the support interference problem for other model configurations.

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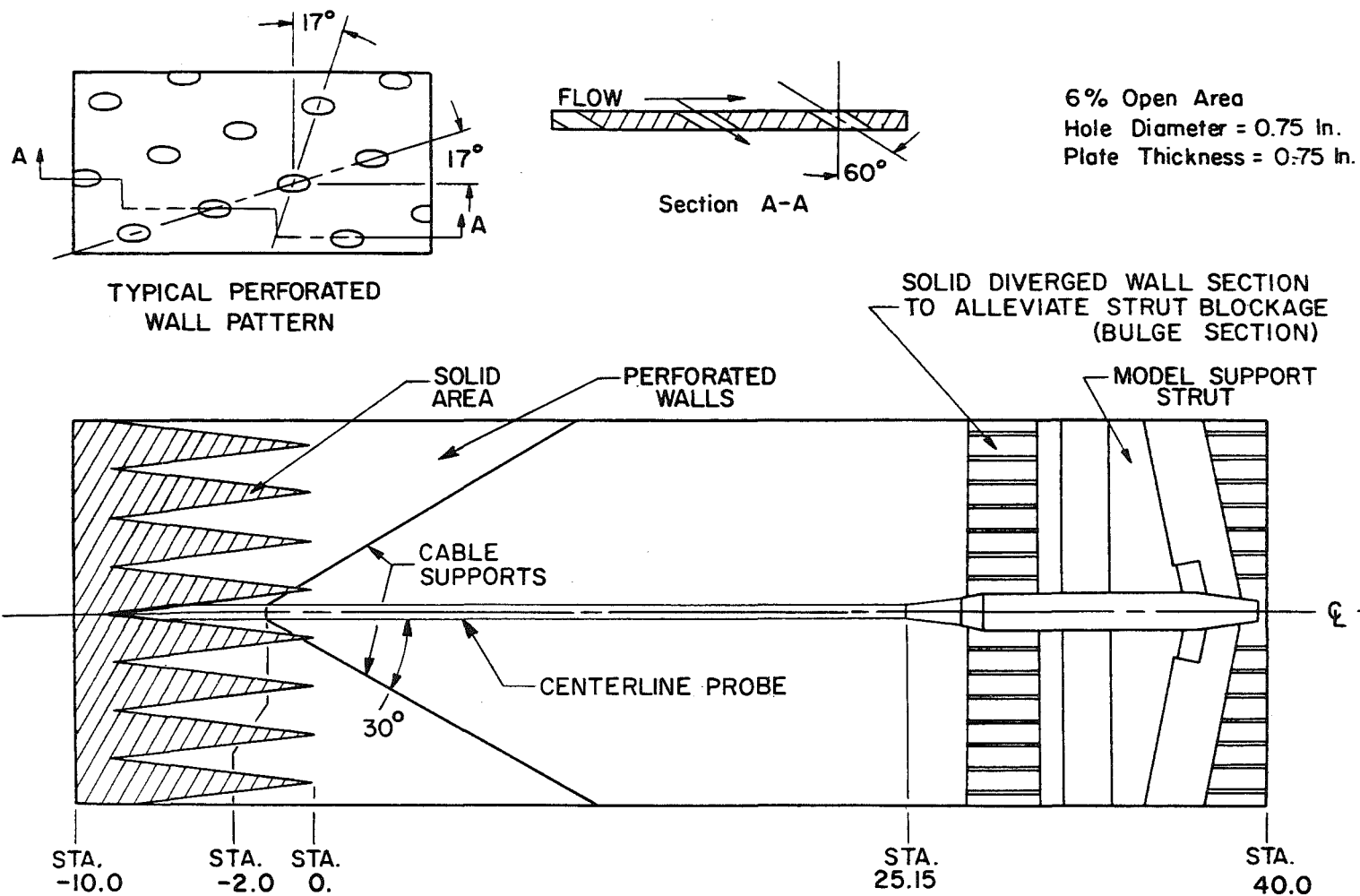


Fig. 1 16-Ft Transonic Circuit Test Section

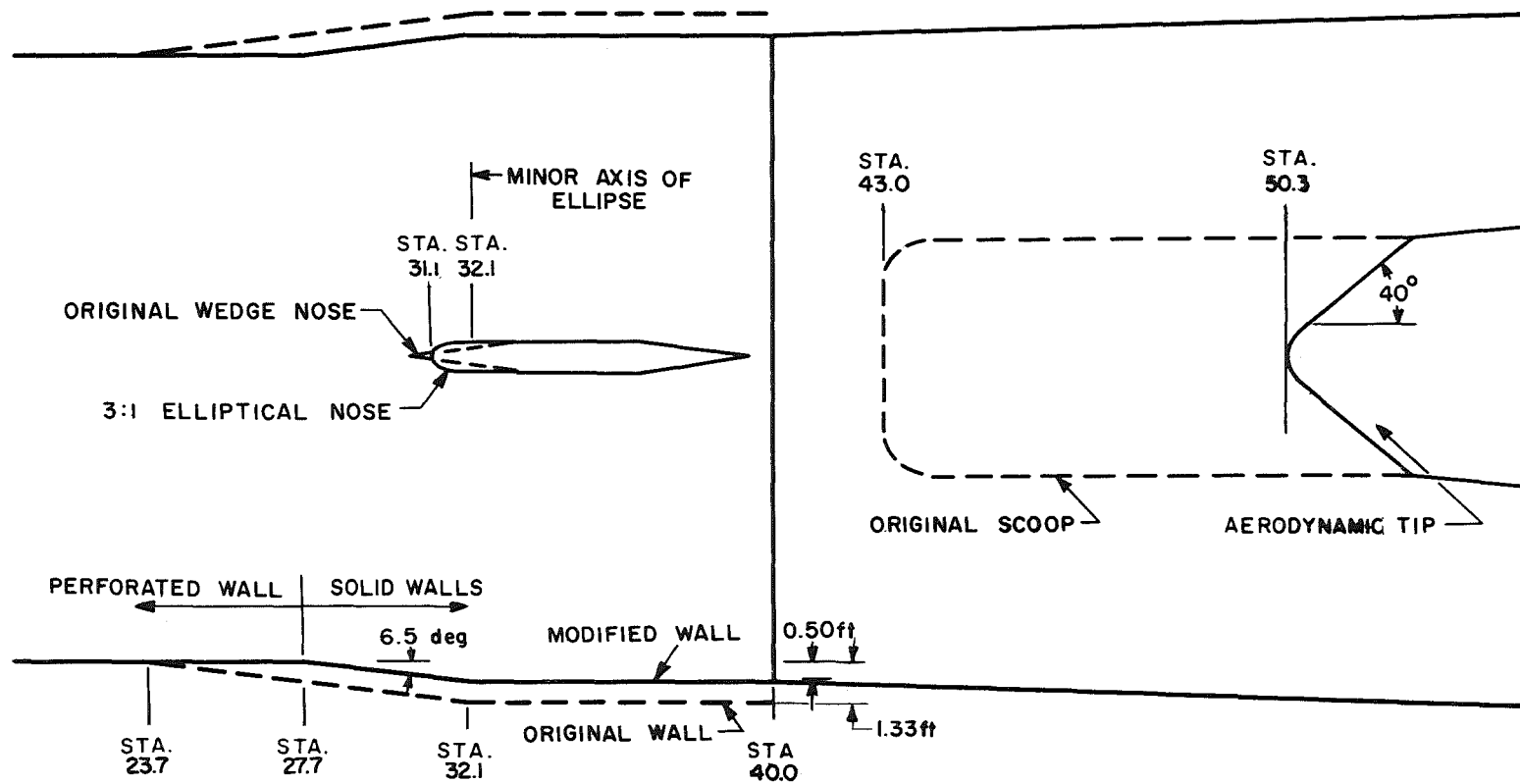
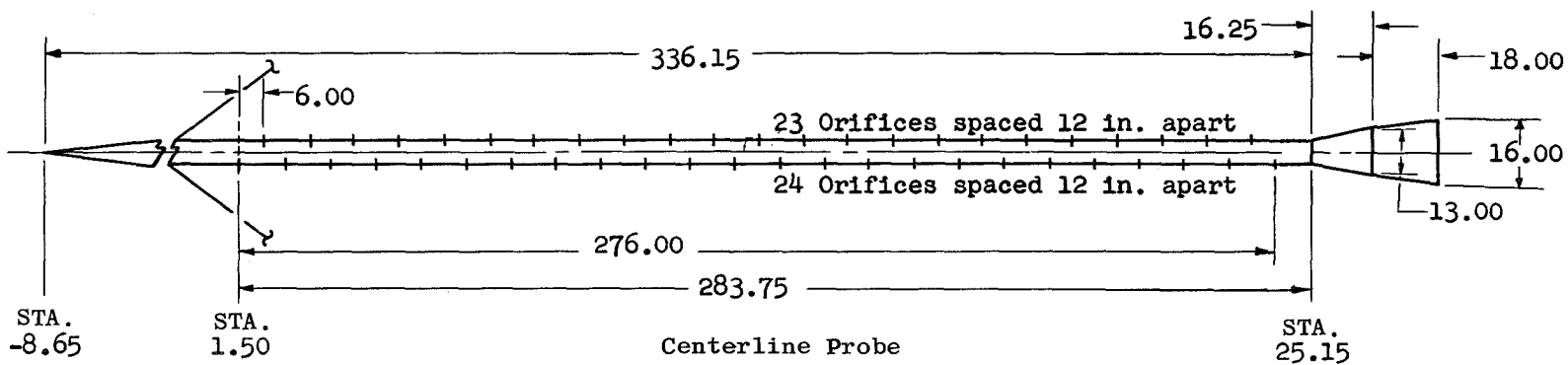
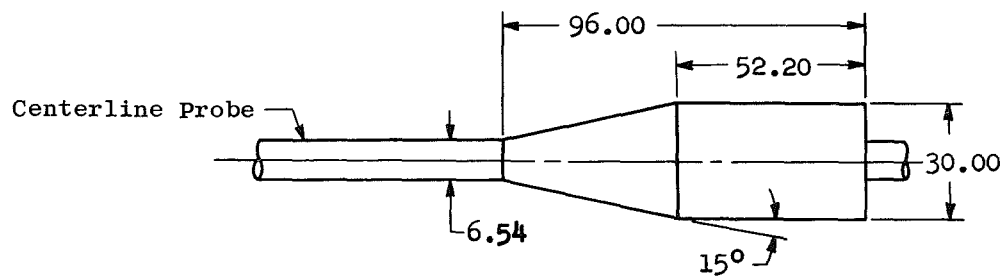


Fig. 2 Modifications to the 16-Ft Transonic Circuit



NOTE: All dimensions in inches



Cone-Cylinder Model

Fig. 3 Centerline Probe and Cone-Cylinder Model

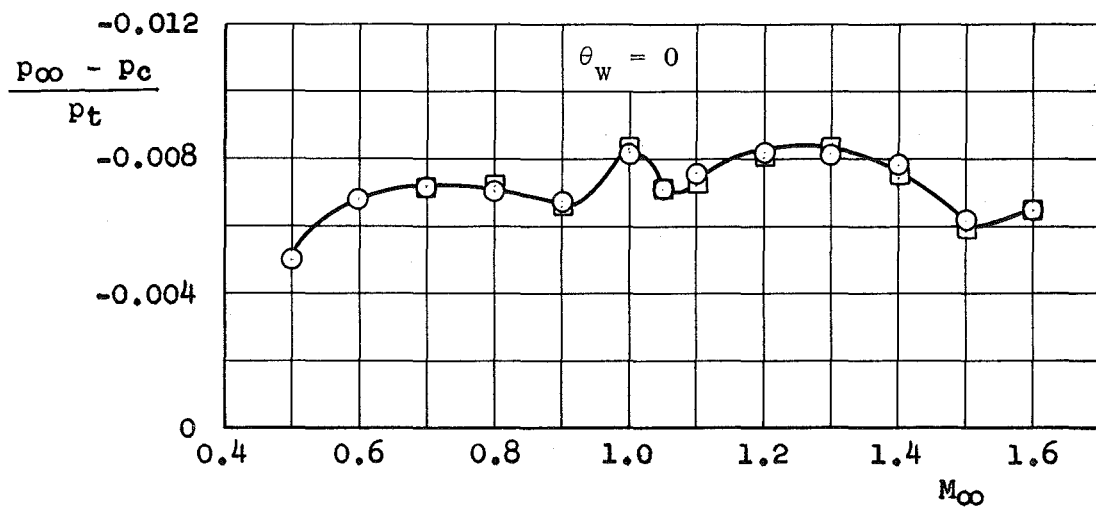
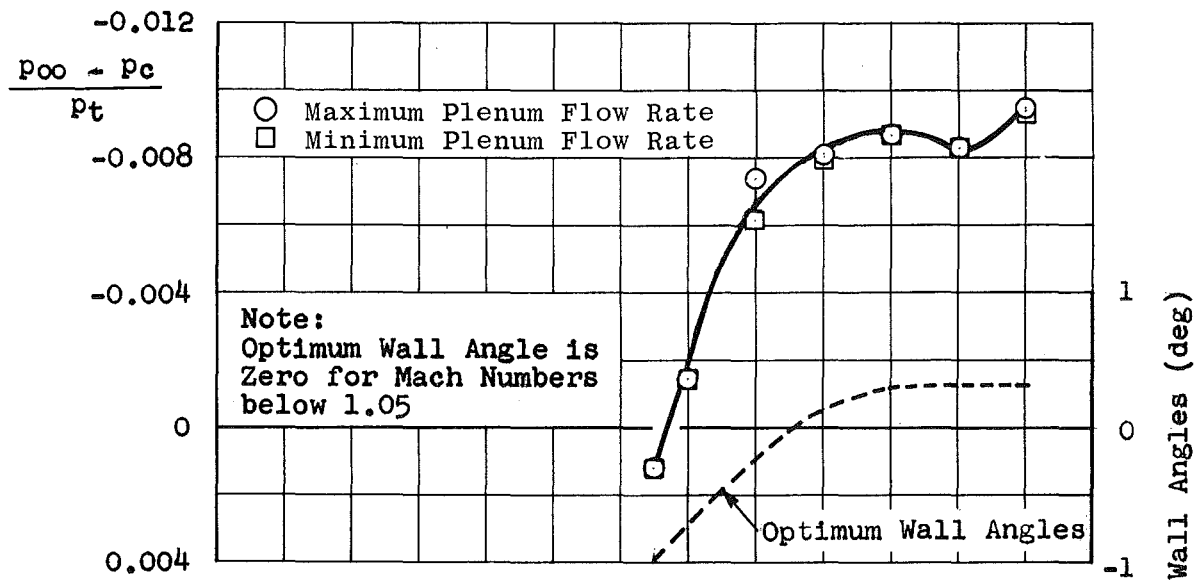
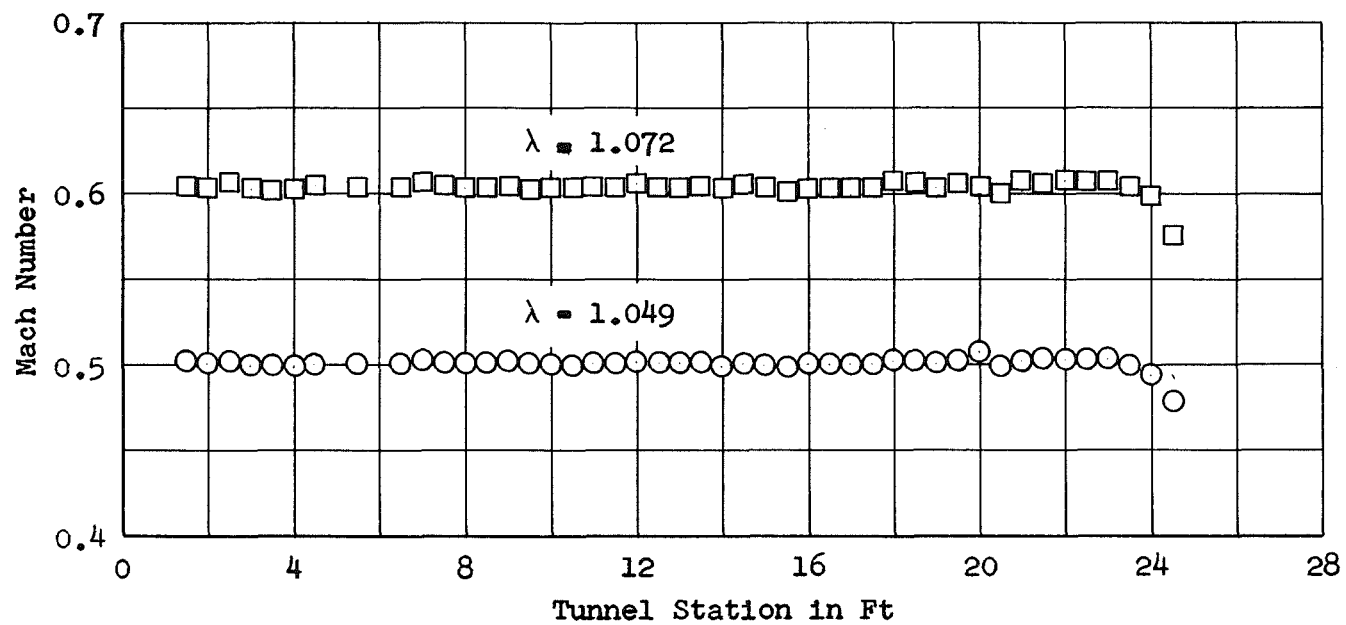
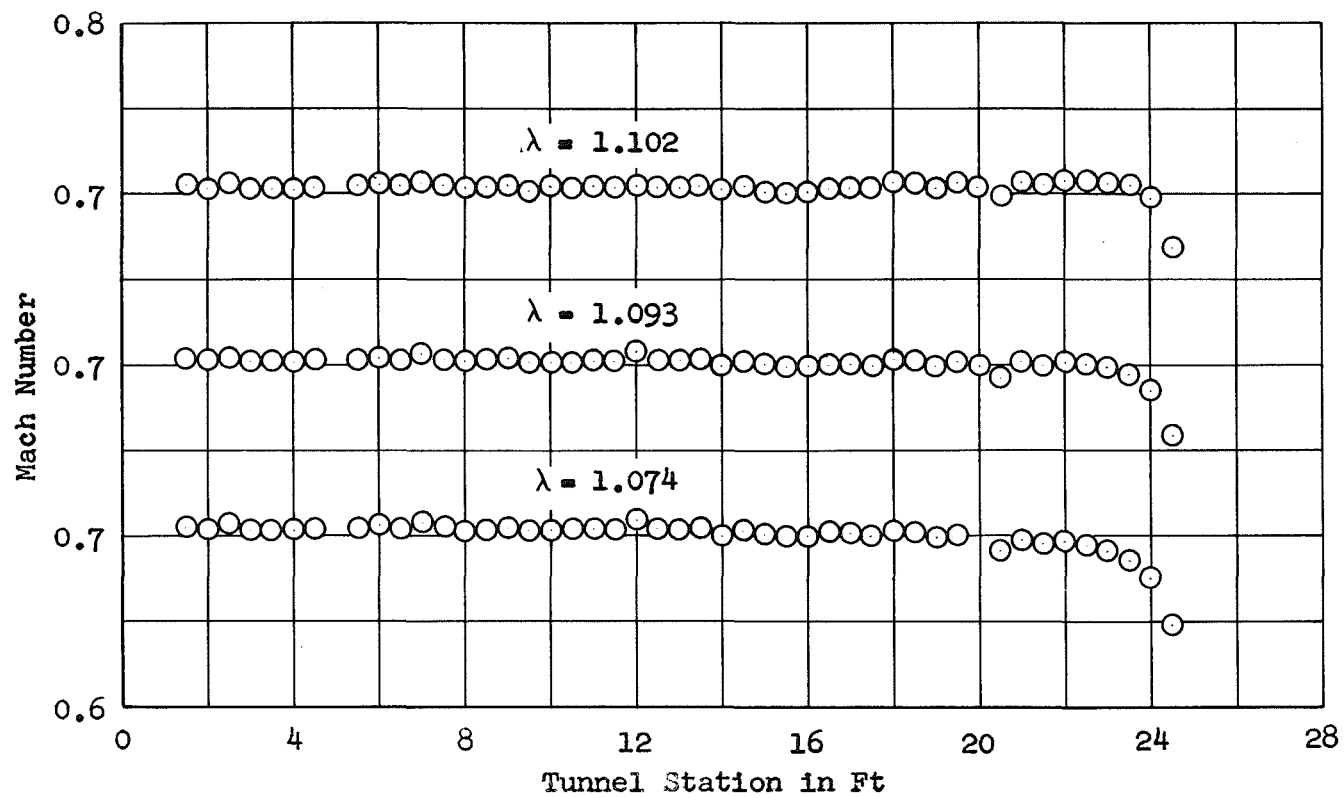


Fig. 4 Variations of Plenum Chamber Pressure Coefficient with Mach Number



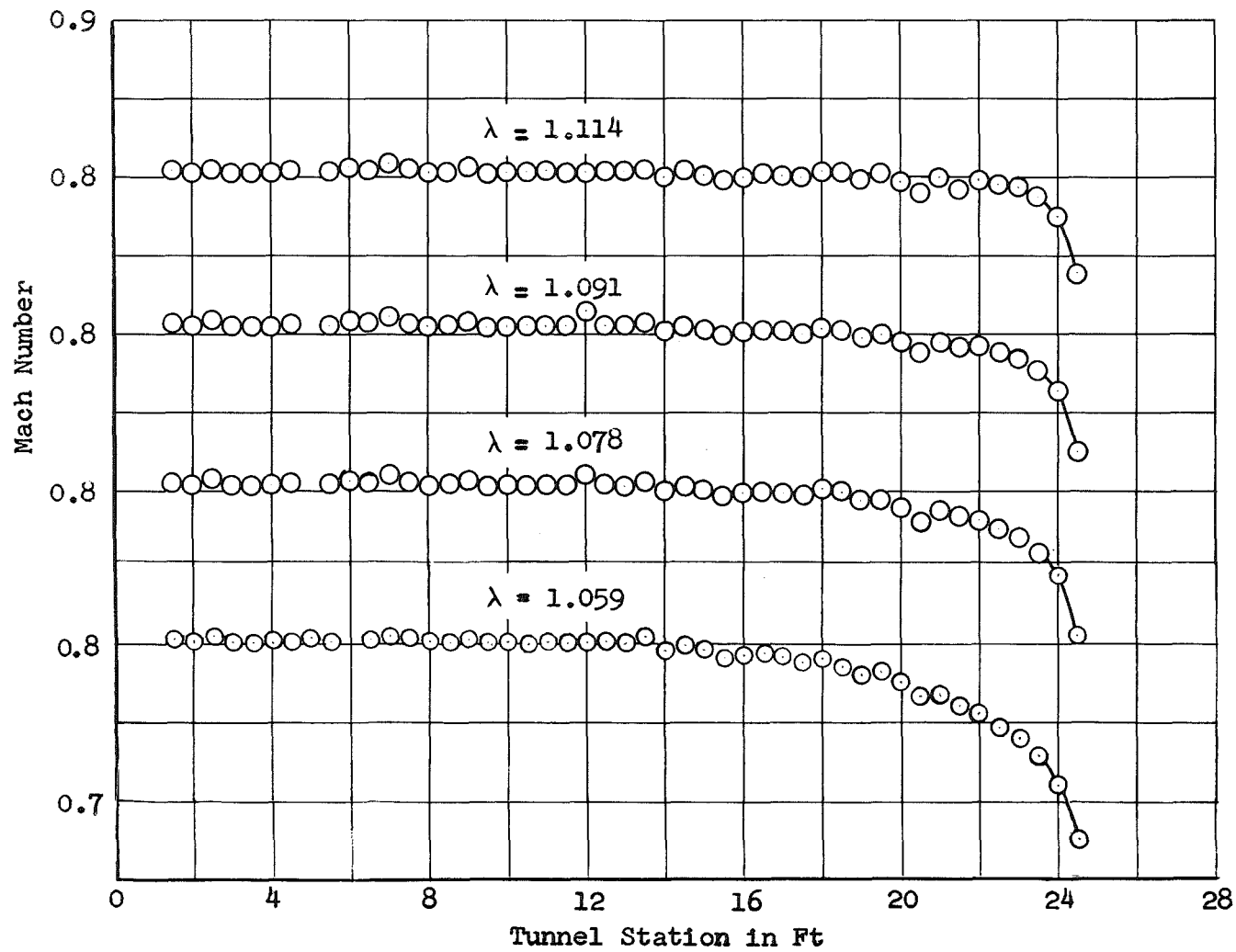
a.  $M_{\infty} = 0.50$  and  $M_{\infty} = 0.60$

Fig. 5 Variations in Mach Number with Tunnel Station for Zero Wall Angle at Various Tunnel Pressure Ratios,  $\theta_w = 0$



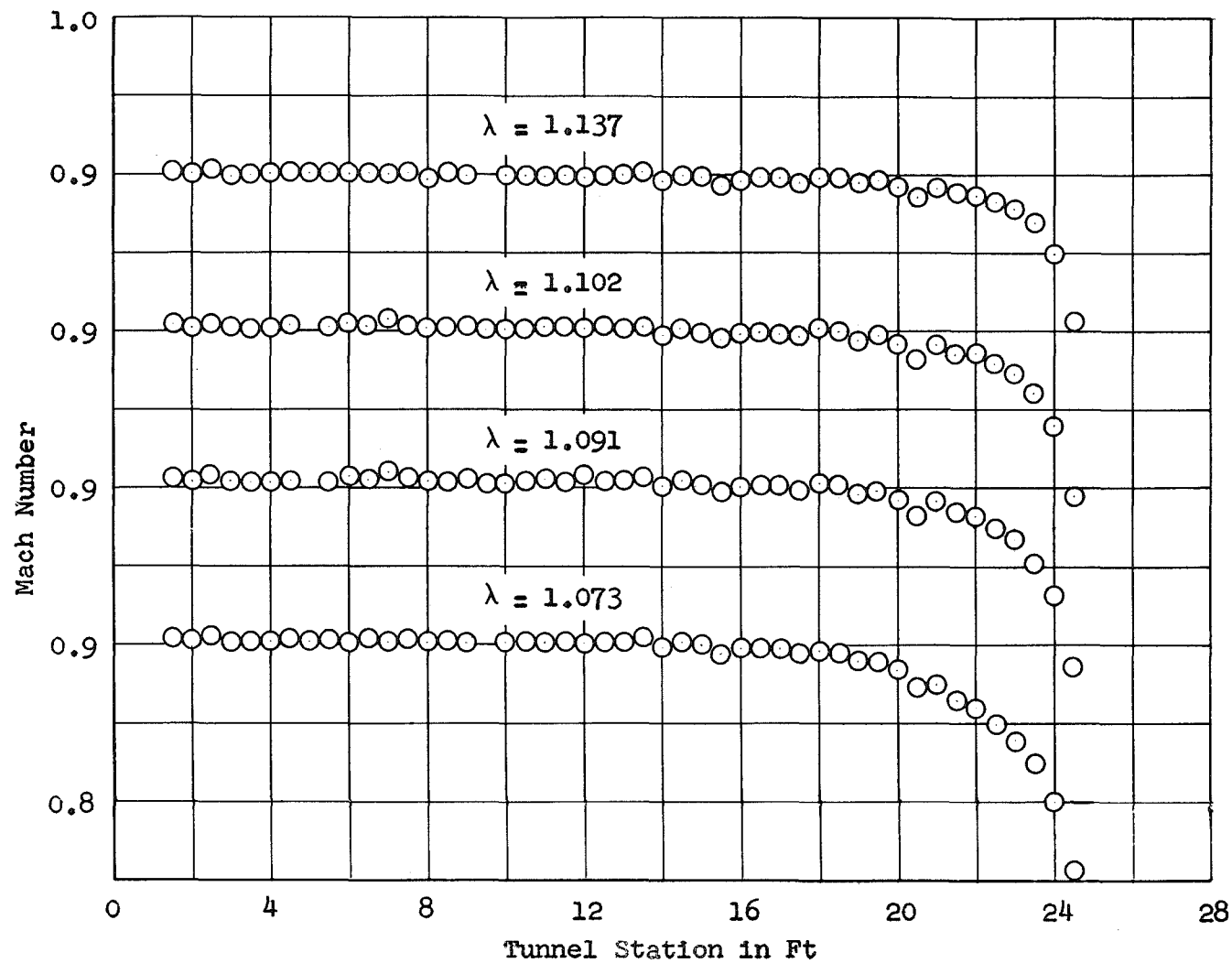
b.  $M_{\infty} = 0.70$

Fig. 5 Continued



c.  $M_{\infty} = 0.80$

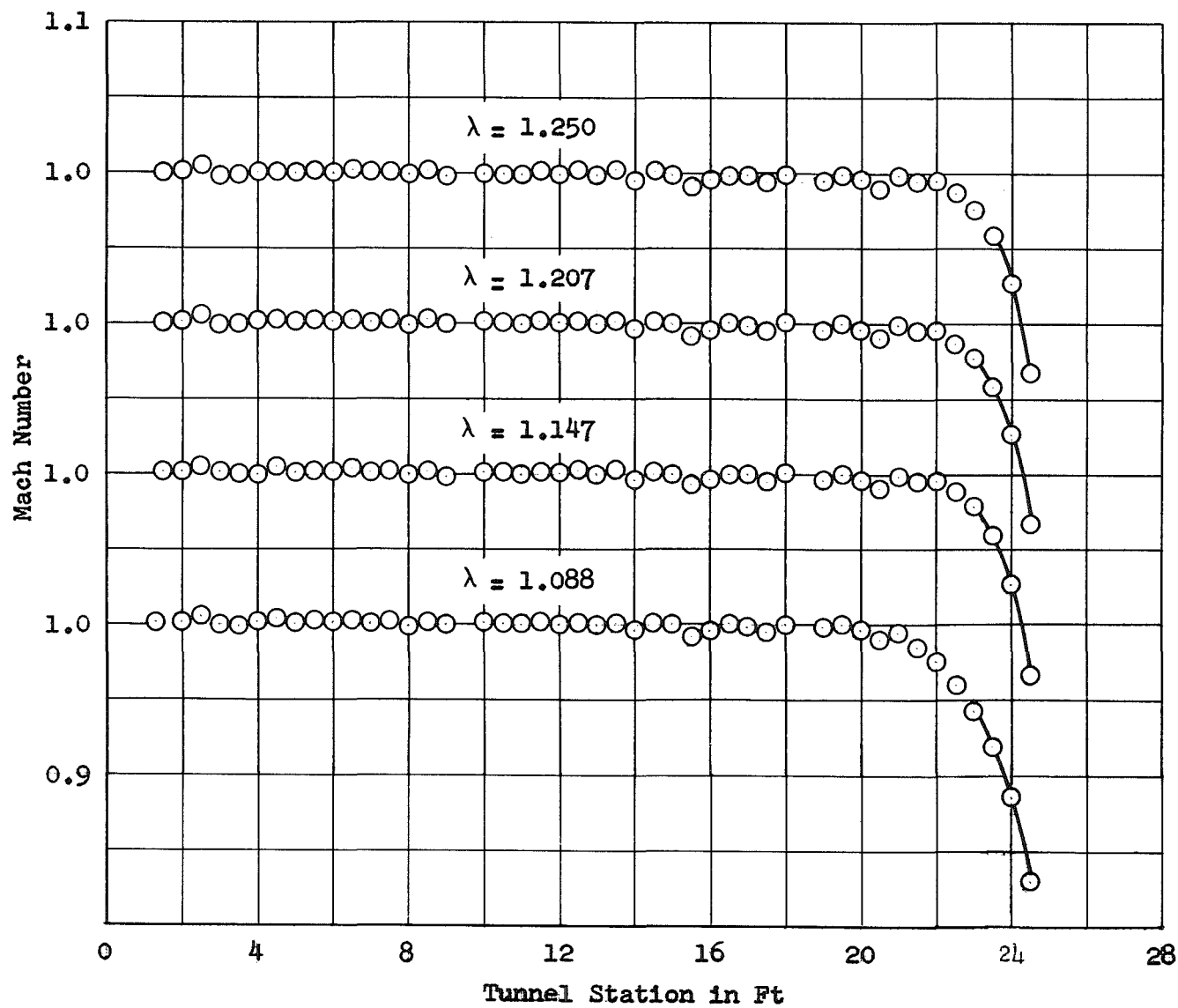
Fig. 5 Continued



d.  $M_{\infty} = 0.90$

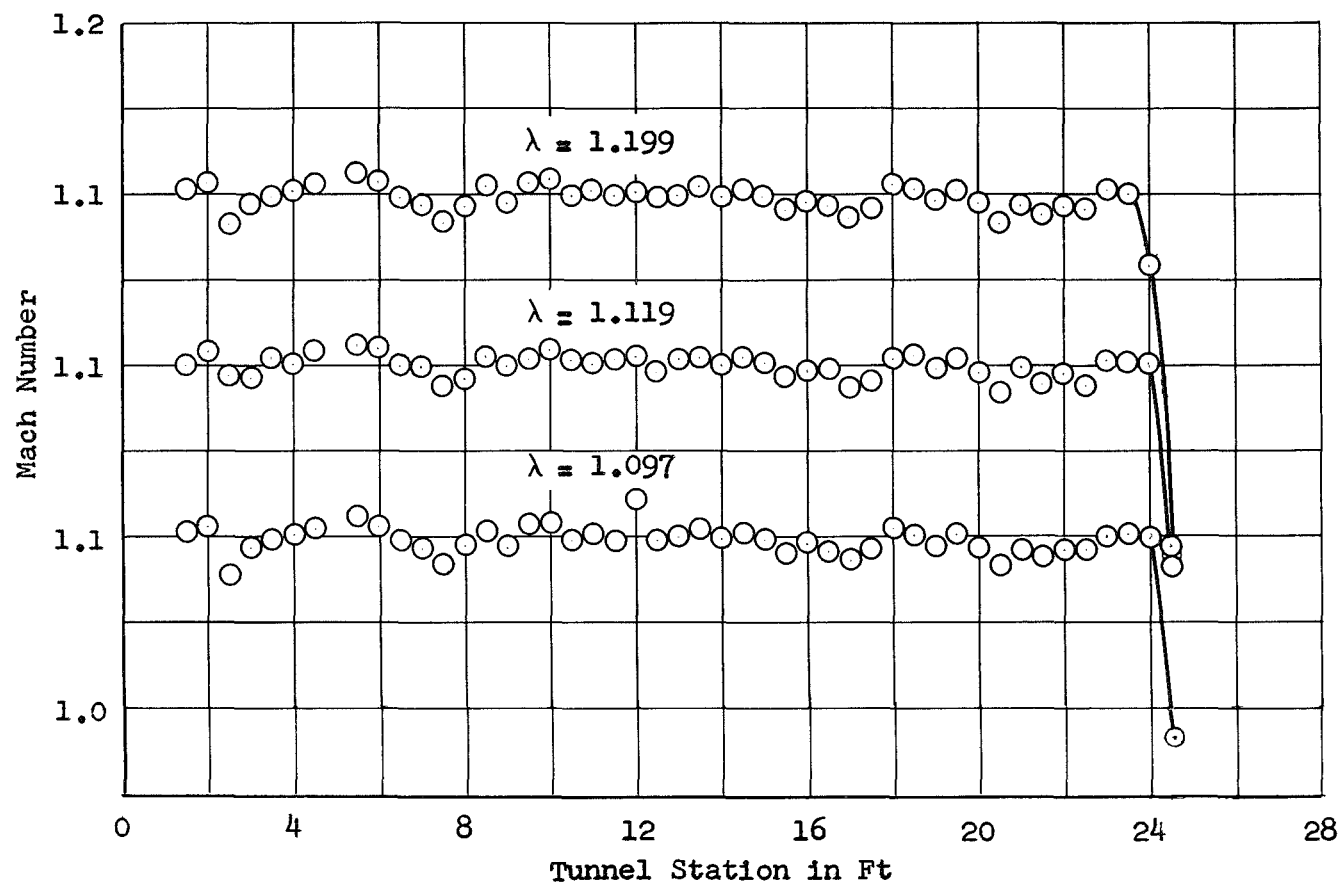
Fig. 5 Continued





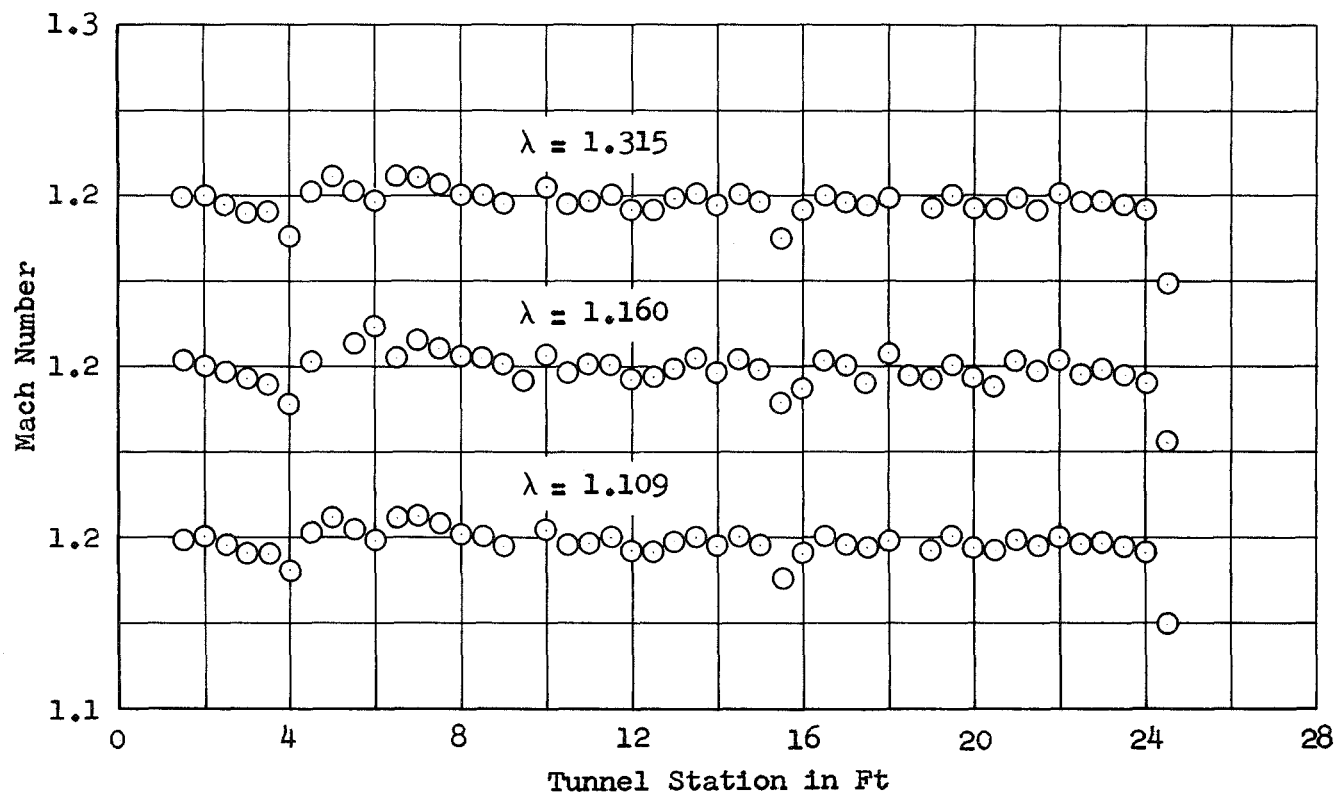
e.  $M_\infty = 1.00$

Fig. 5 Continued

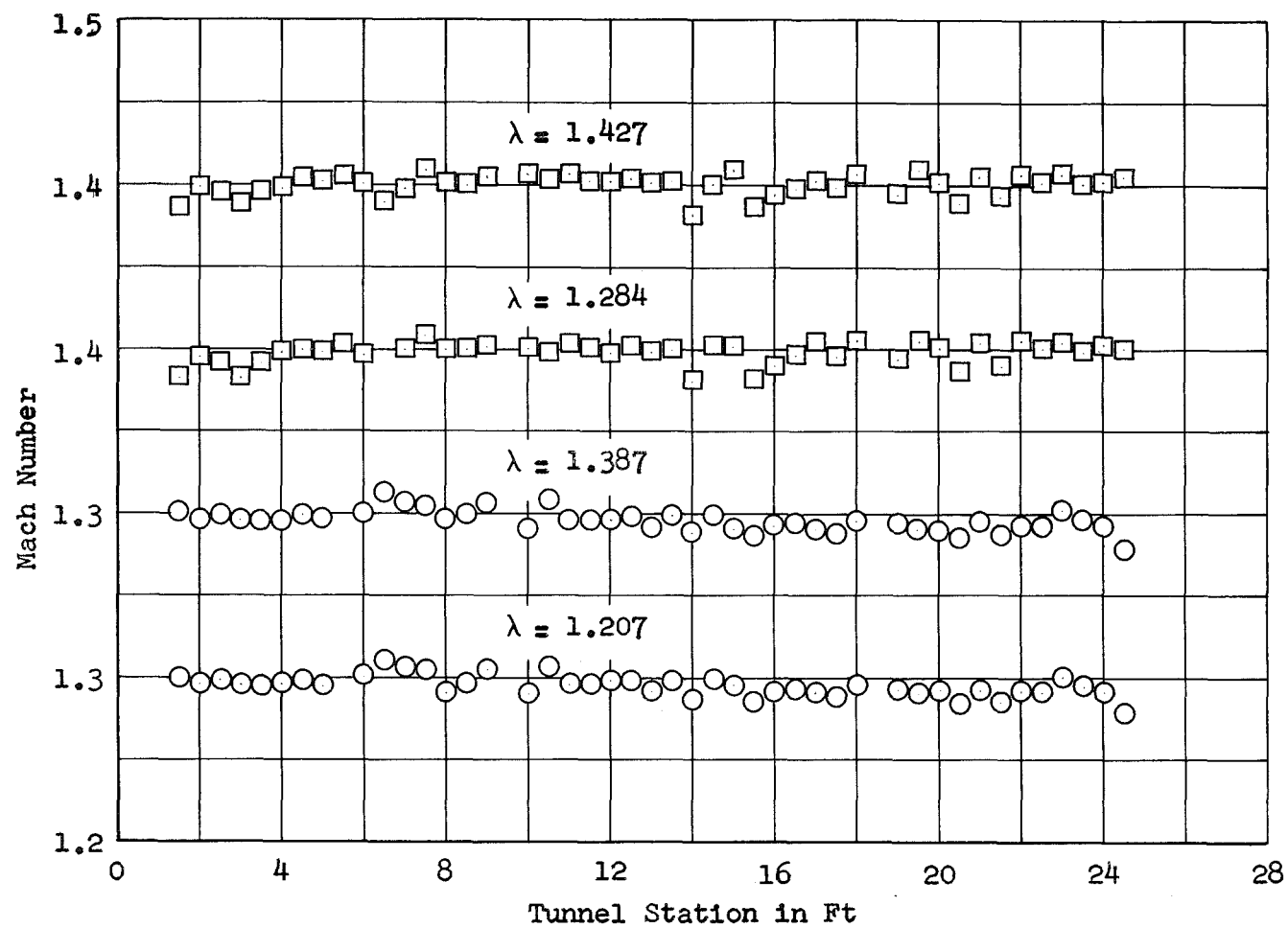


f.  $M_{\infty} = 1.10$

Fig. 5 Continued

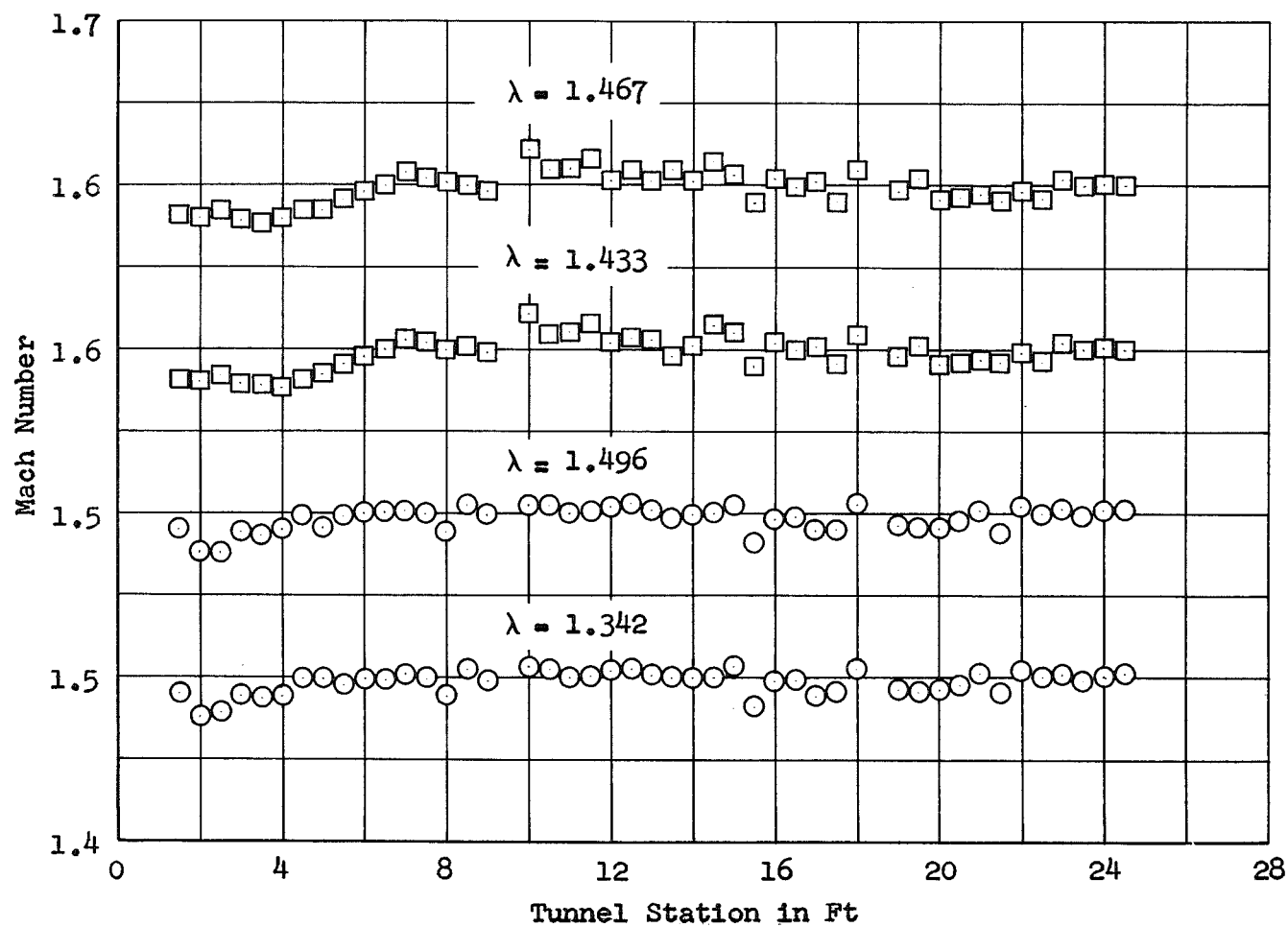


g.  $M_{\infty} = 1.20$   
 Fig. 5 Continued



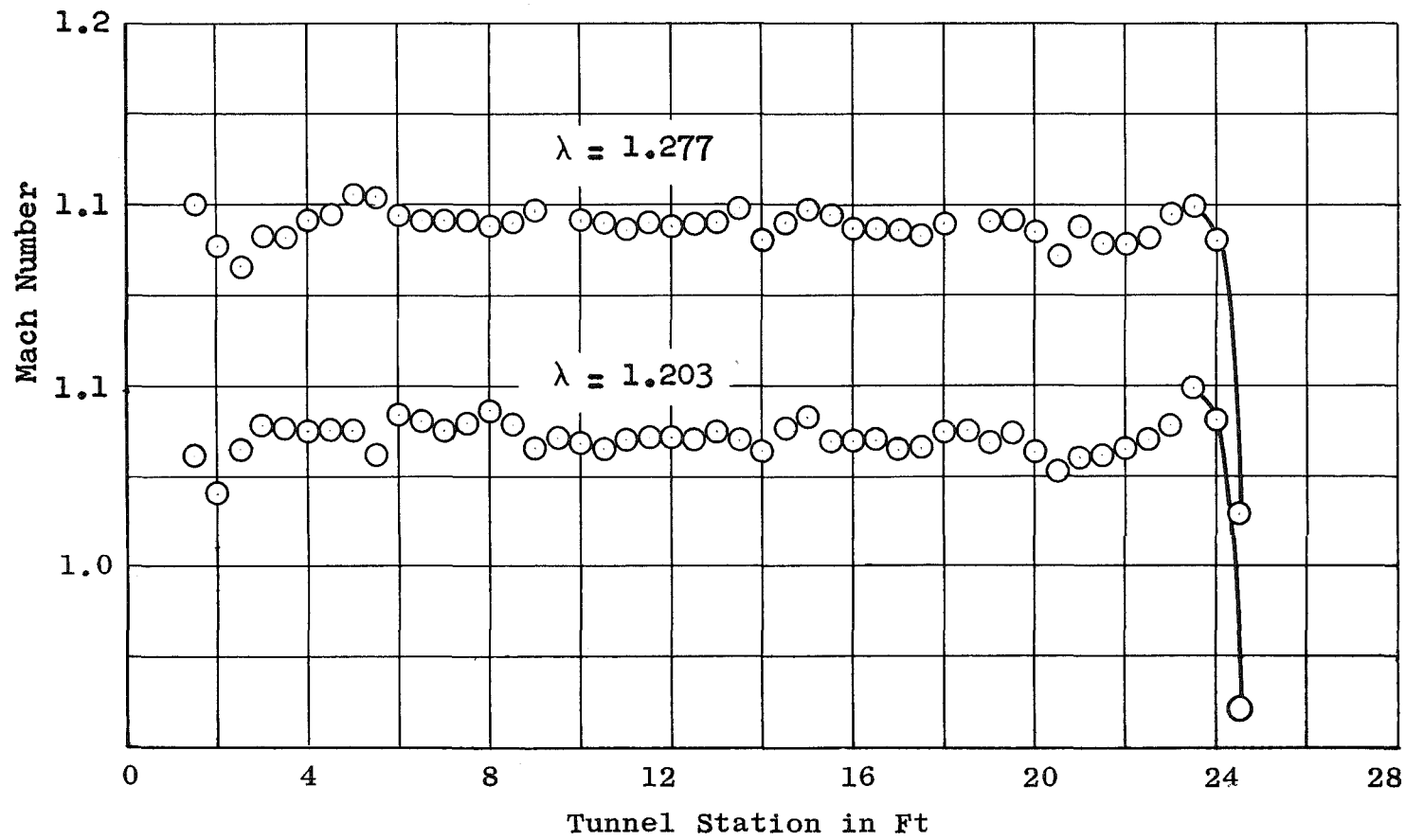
h.  $M_{\infty} = 1.30$  and  $M_{\infty} = 1.40$

Fig. 5 Continued



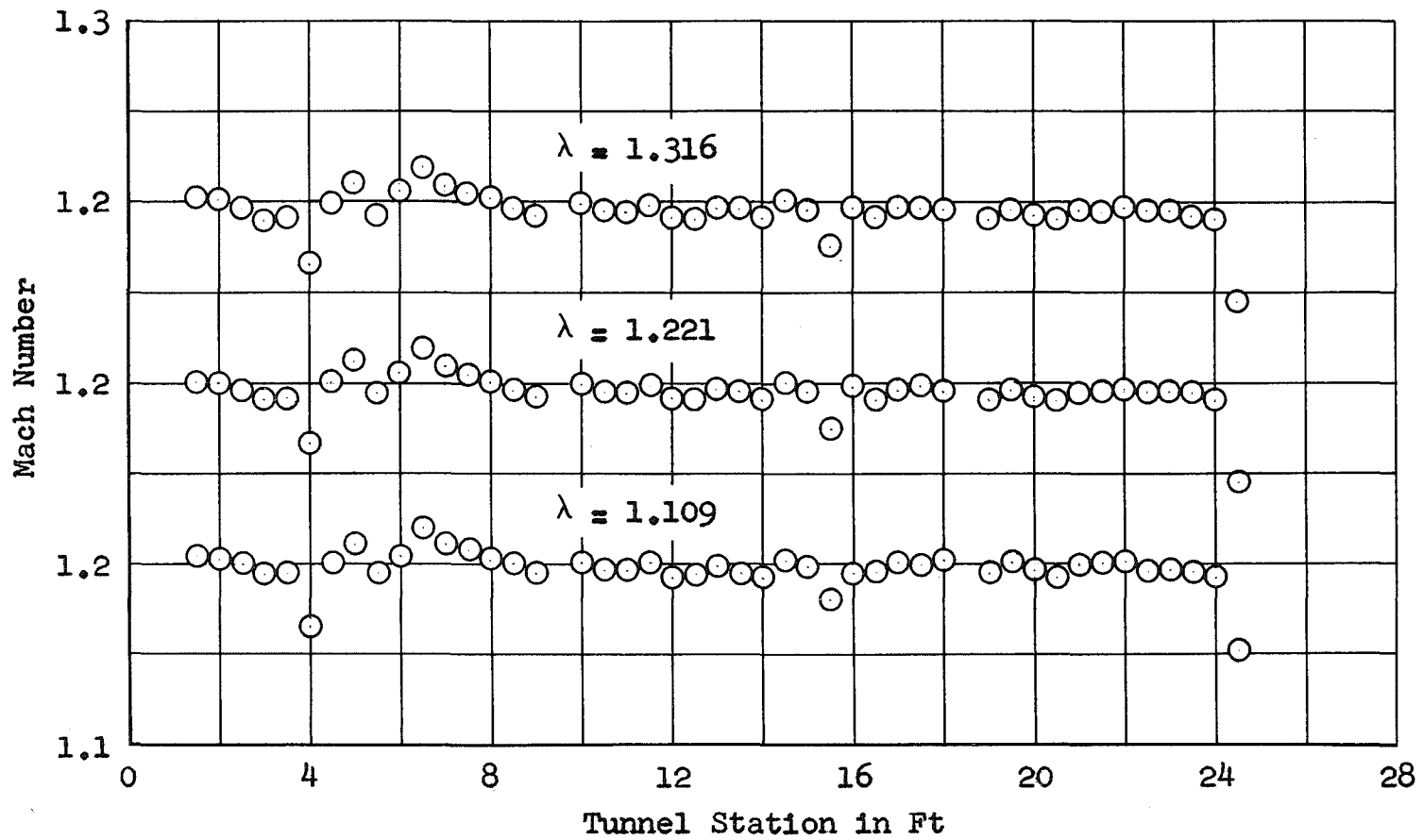
i.  $M_{\infty} = 1.50$  and  $M_{\infty} = 1.60$

Fig. 5 Concluded



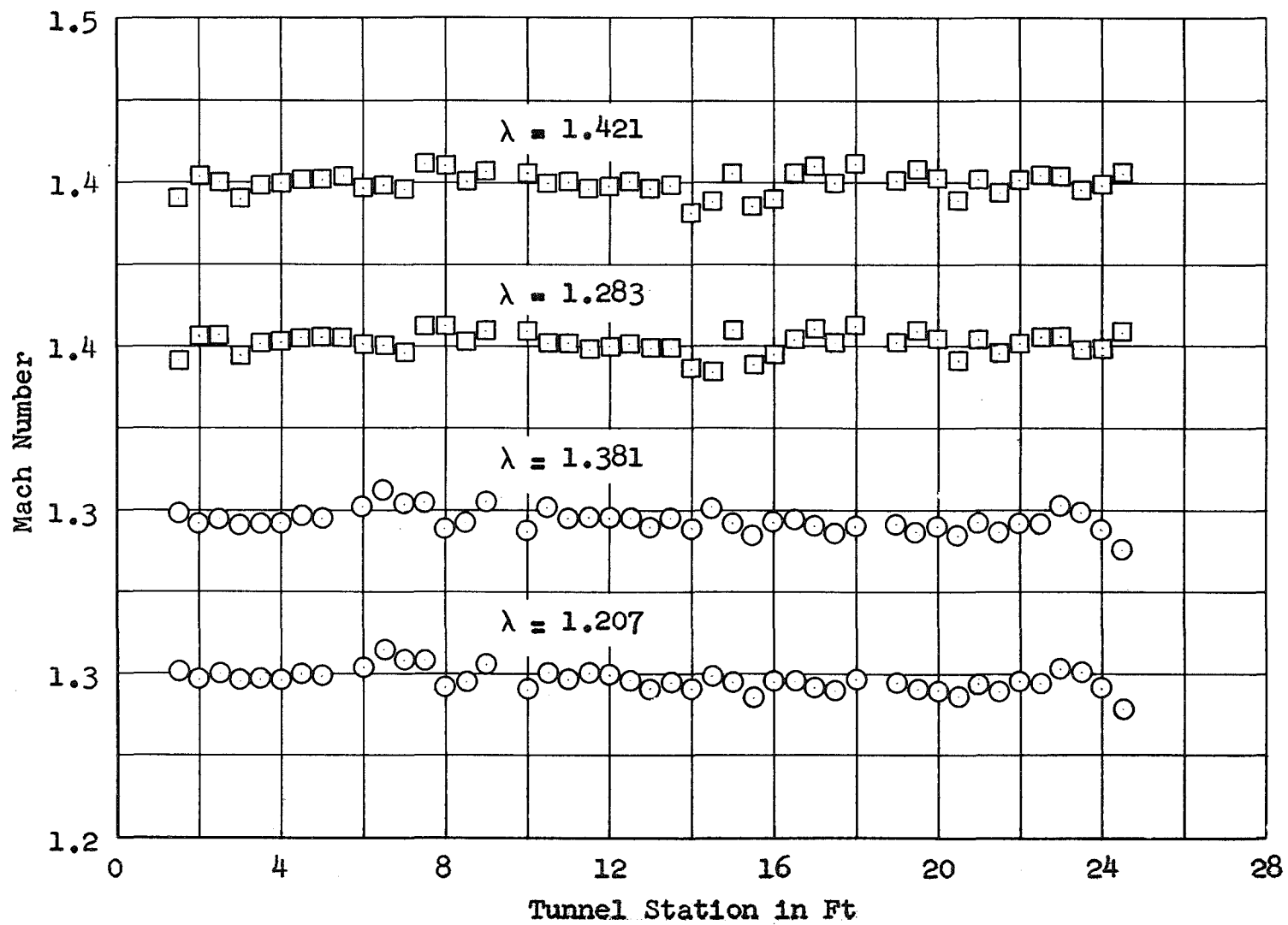
a.  $M_{\infty} = 1.10, \theta_w = -0.75$

Fig. 6 Variations in Mach Number with Tunnel Station for Optimum Wall Angles at Various Tunnel Pressure Ratios



b.  $M_{\infty} = 1.20$ ,  $\theta_w = -0.25$

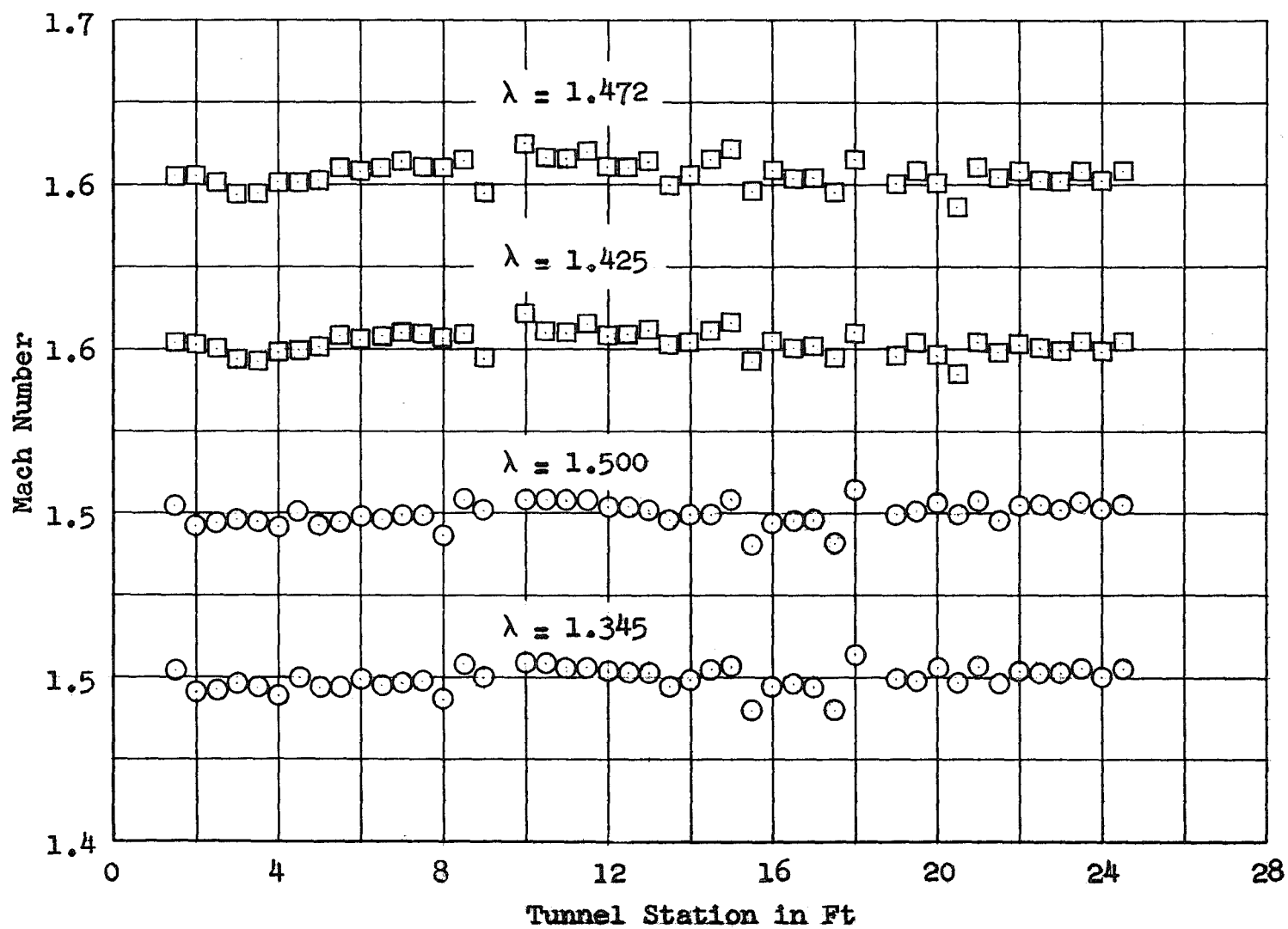
Fig. 6 Continued



c.  $M_{\infty} = 1.30$ ,  $\theta_w = 0.15$  and  $M_{\infty} = 1.40$ ,  $\theta_w = 0.25$

Fig. 6 Continued





d.  $M_{\infty} = 1.50$ ,  $\theta_w = 0.30$  and  $M_{\infty} = 1.60$ ,  $\theta_w = 0.30$

Fig. 6 Concluded

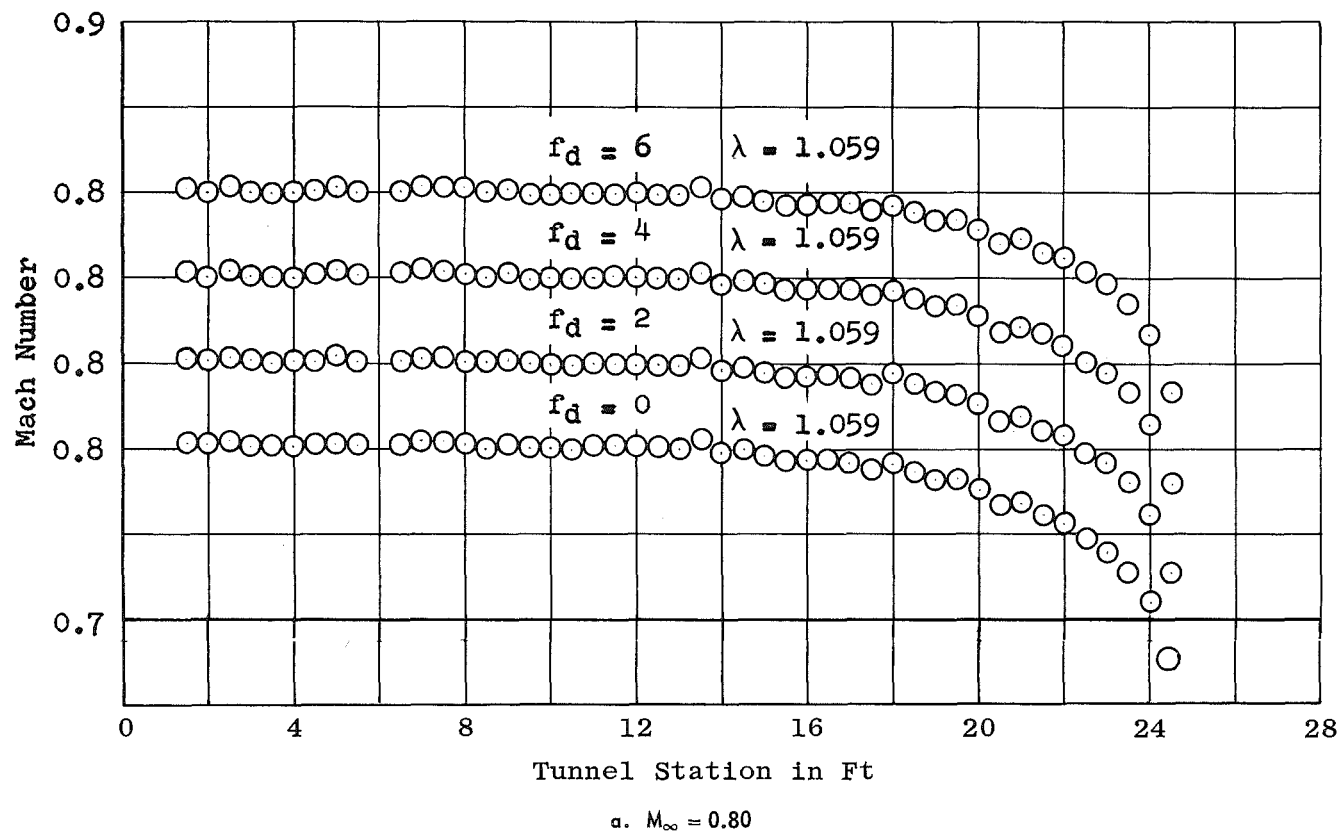
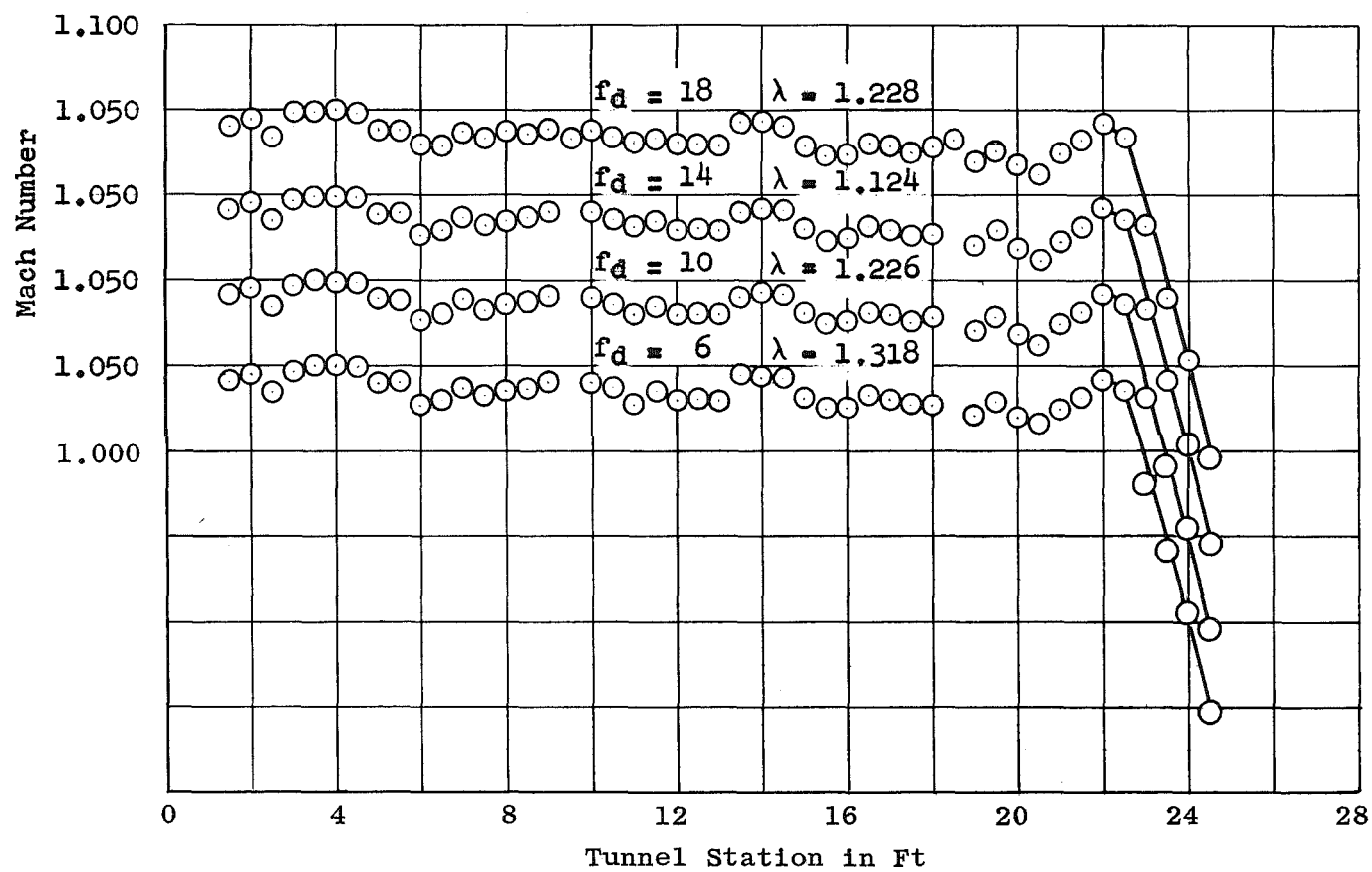
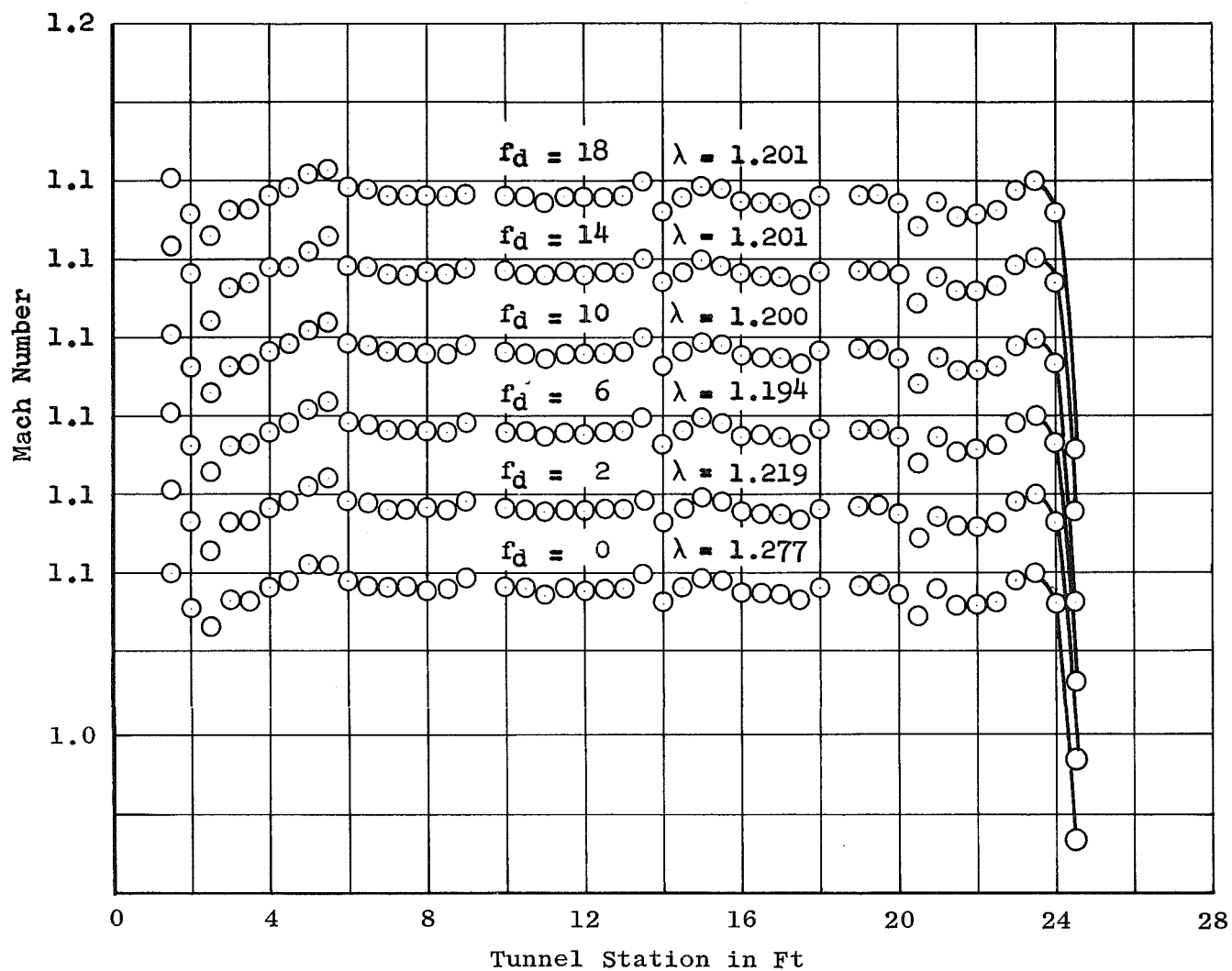


Fig. 7 Variations in Mach Number with Tunnel Station for Various Diffuser Flap Openings



b.  $M_\infty = 1.50$ ,  $\theta_w = -1.0$

Fig. 7 Continued



c.  $M_\infty = 1.10, \theta_w = -0.75$

Fig. 7 Concluded

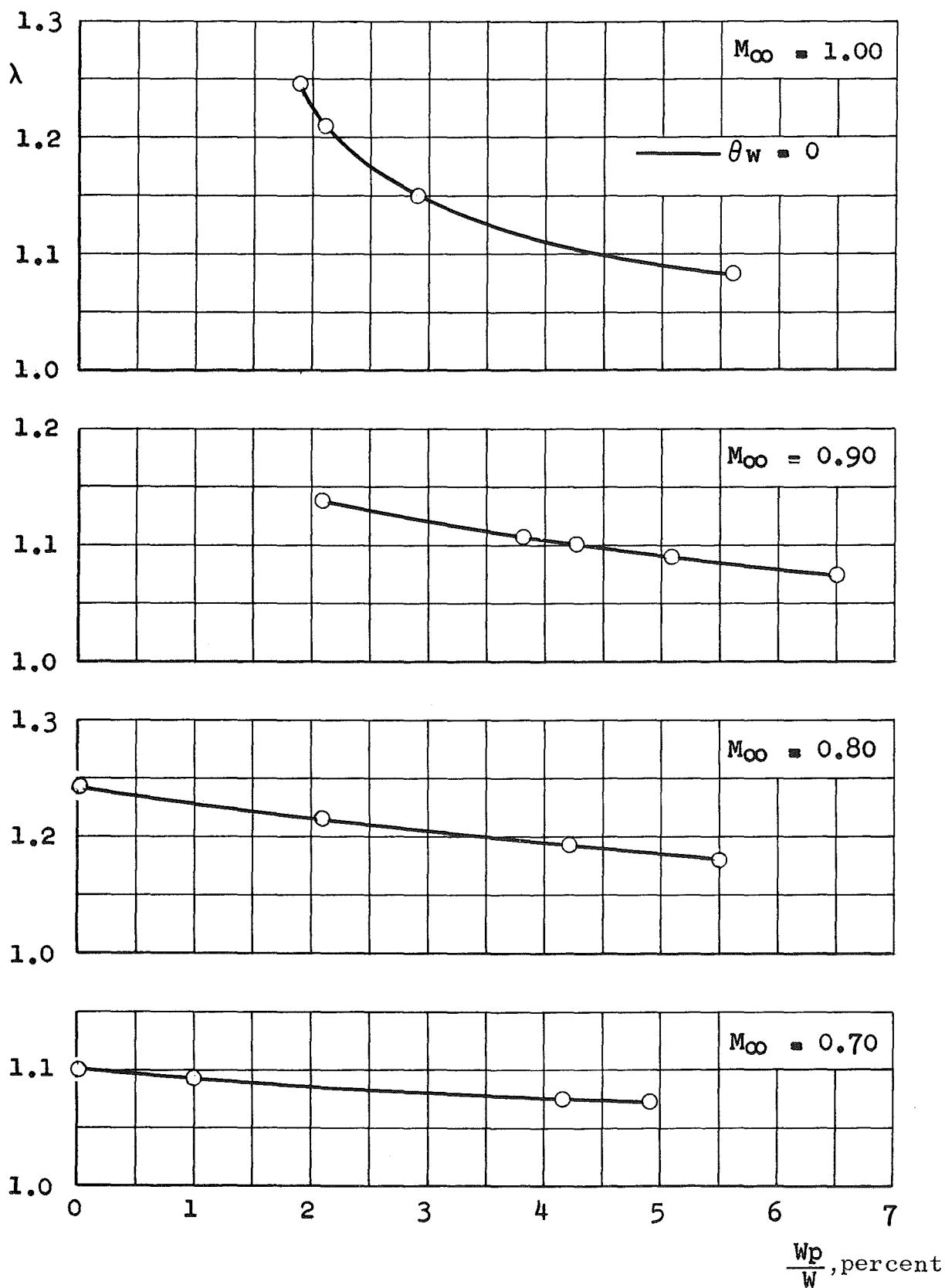


Fig. 8 Variation of Tunnel Pressure Ratio with Plenum Auxiliary Section

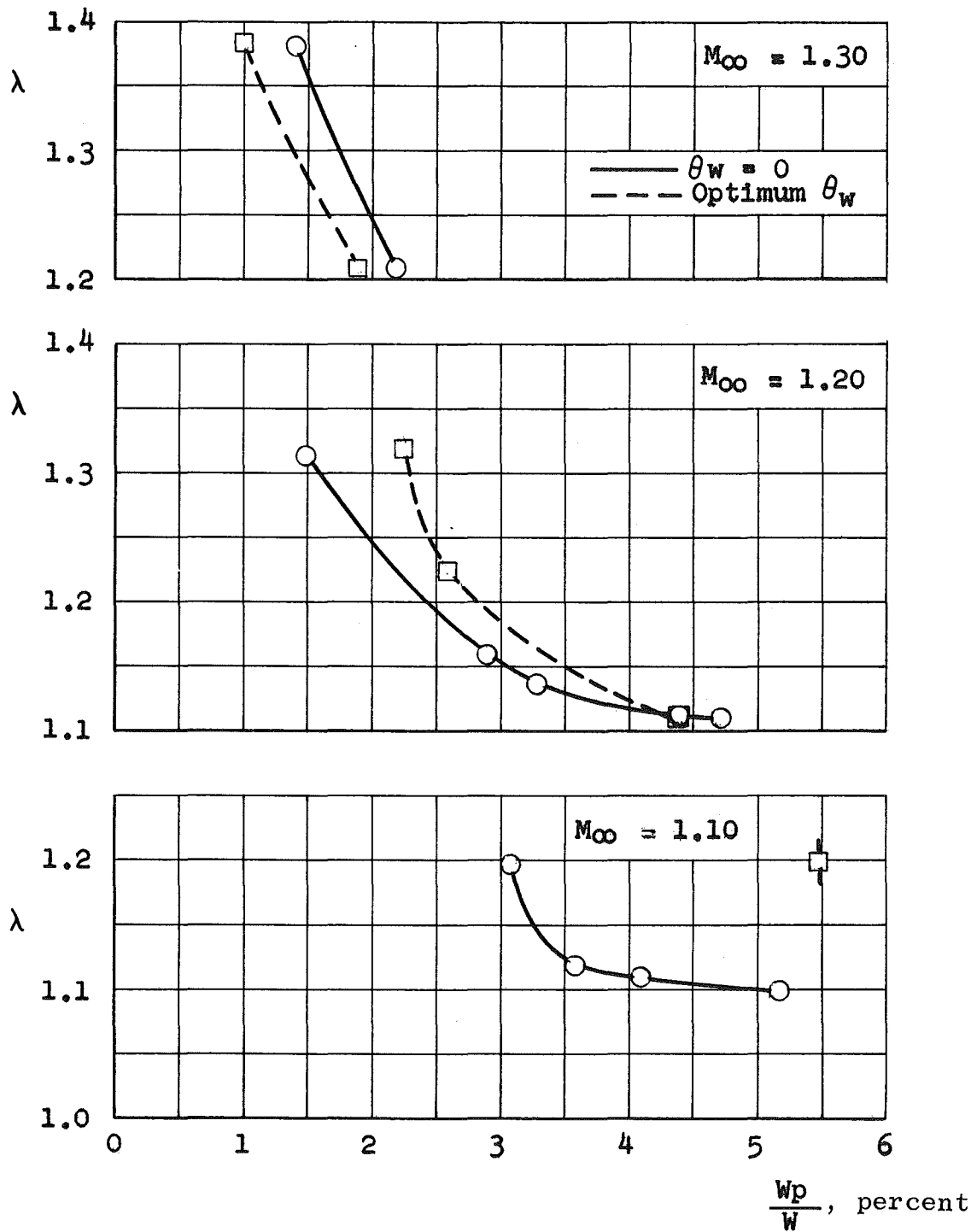


Fig. 8 Continued

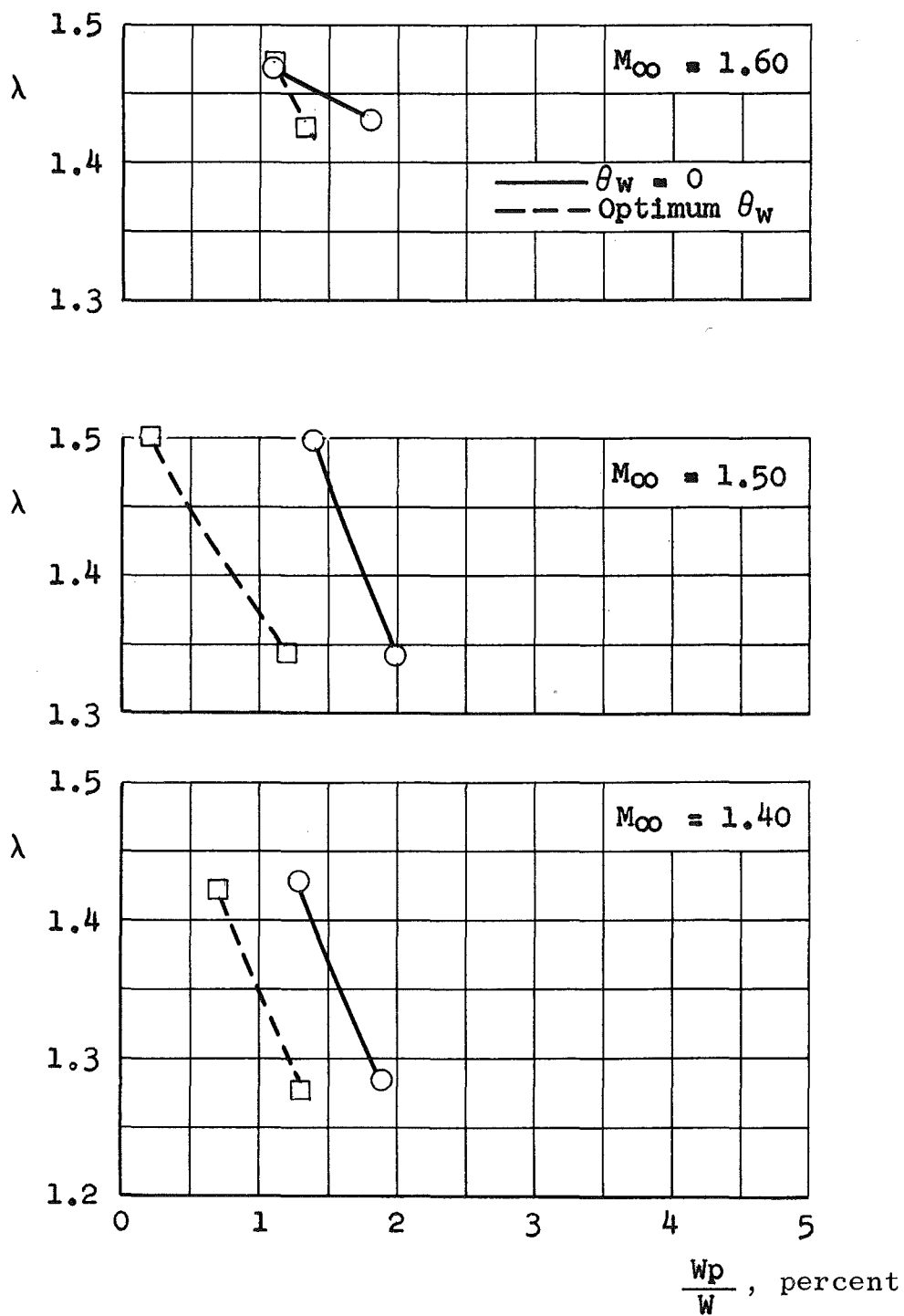


Fig. 8 Concluded

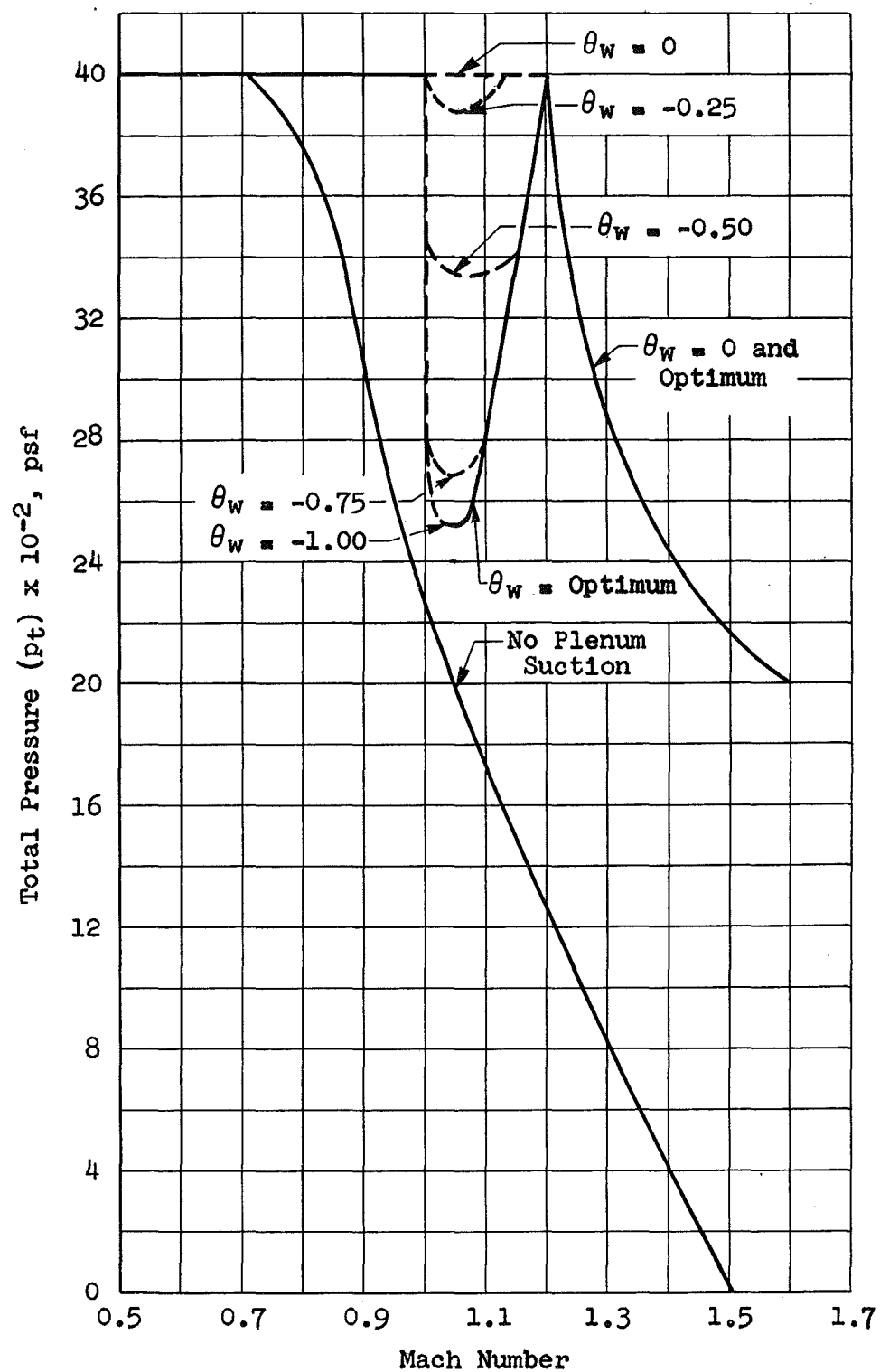


Fig. 9 Variation of Maximum Tunnel Total Pressure with Mach Number



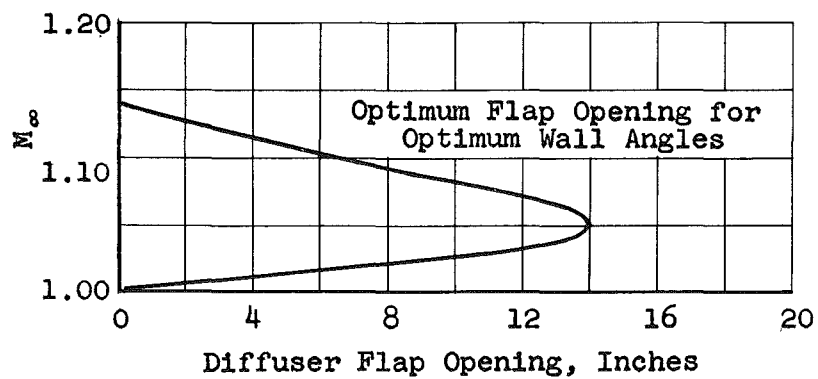
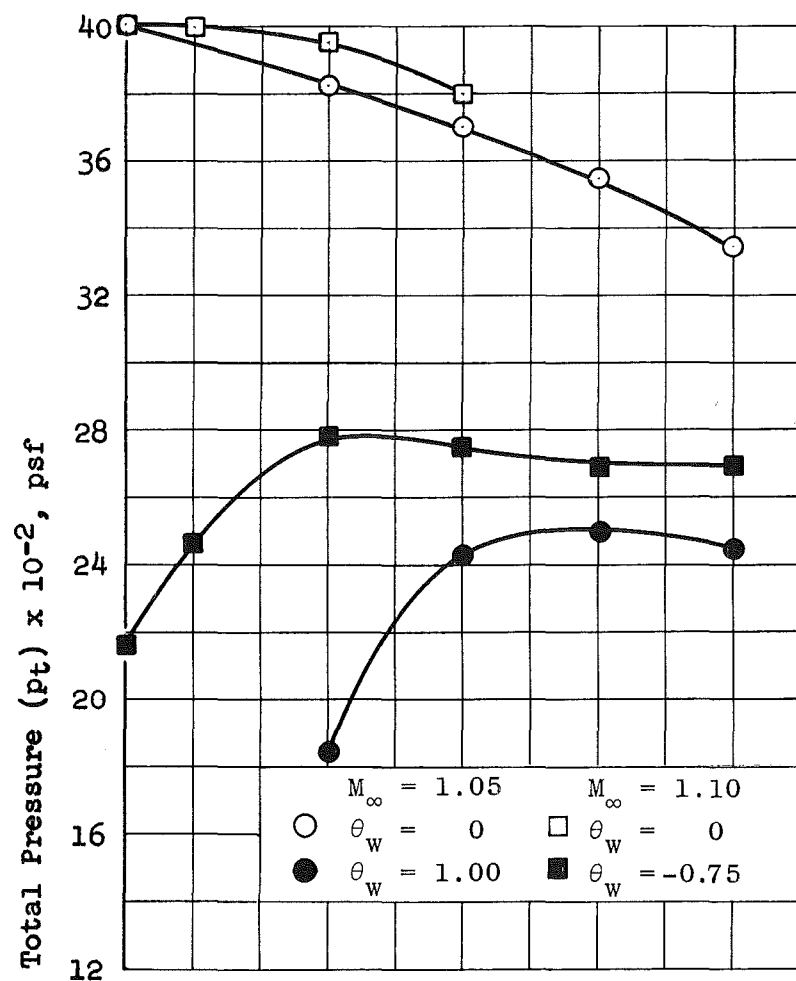


Fig. 10 Variation of Maximum Tunnel Total Pressure with Diffuser Flap Opening

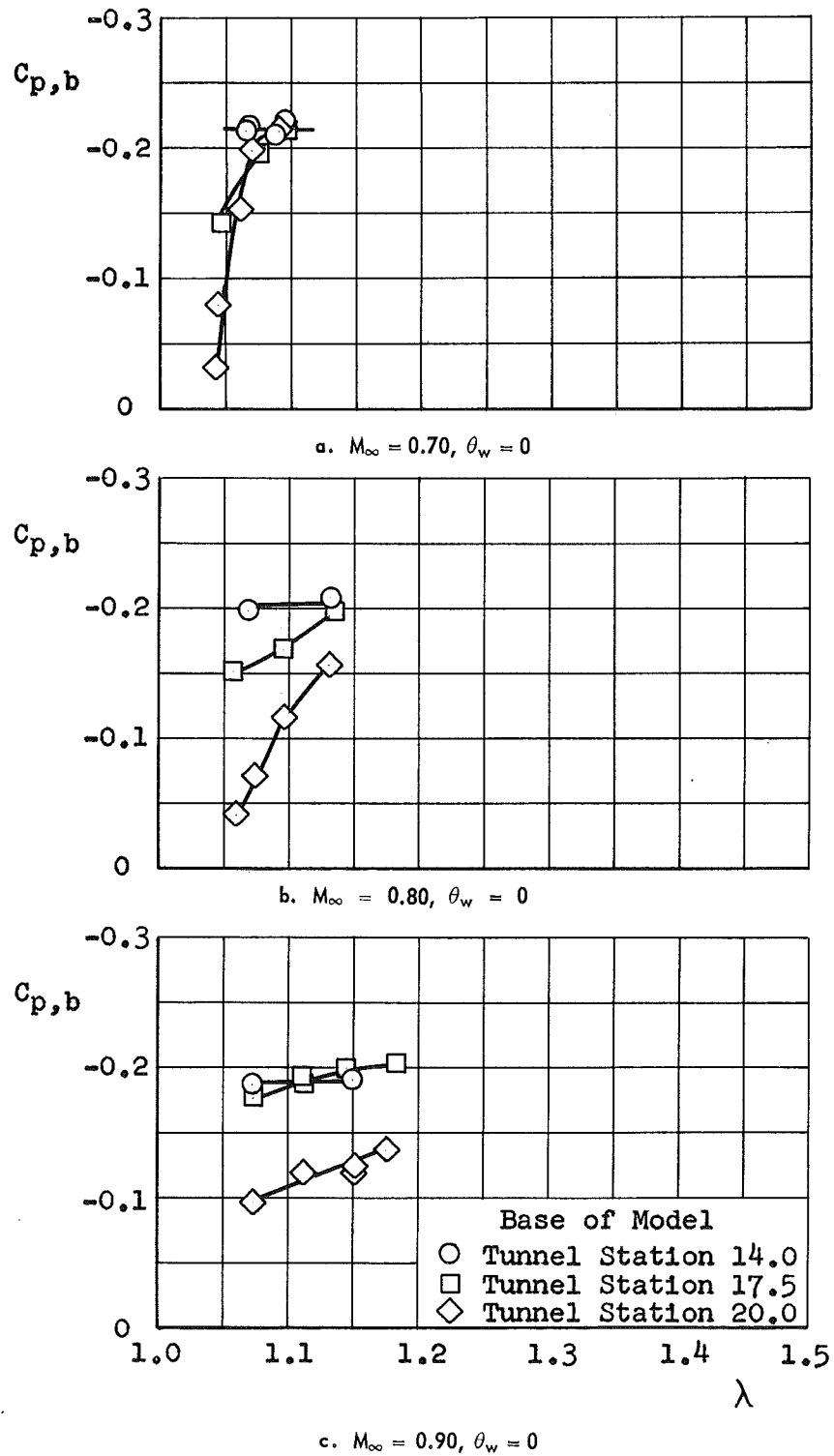


Fig. 11 Variation of Model Base Pressure Coefficient with Tunnel Pressure Ratio

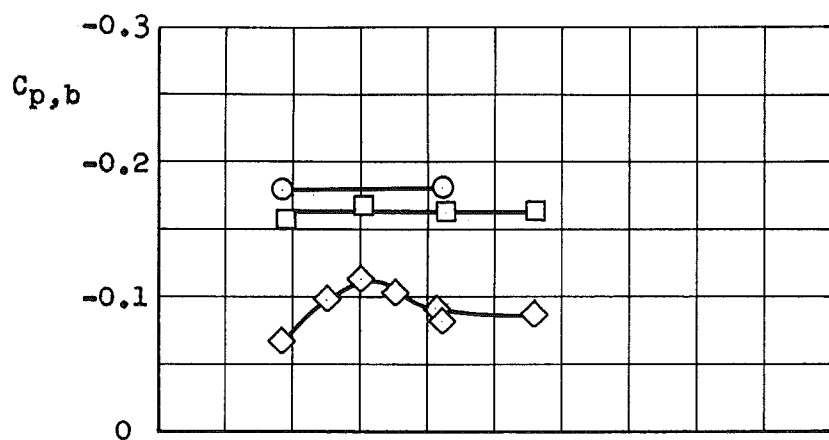
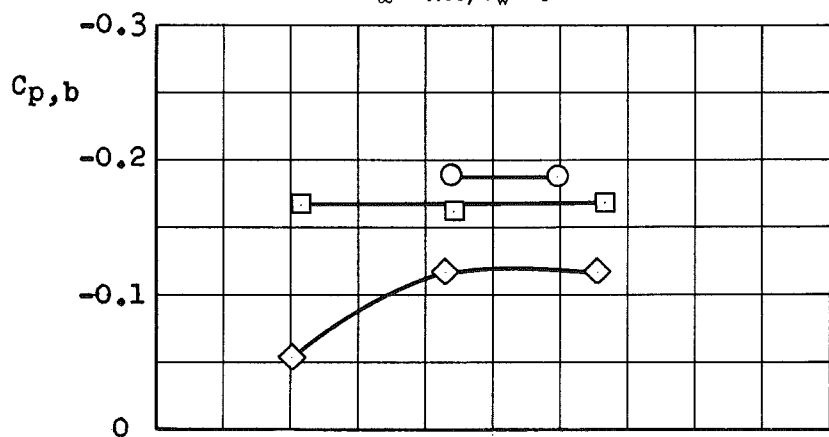
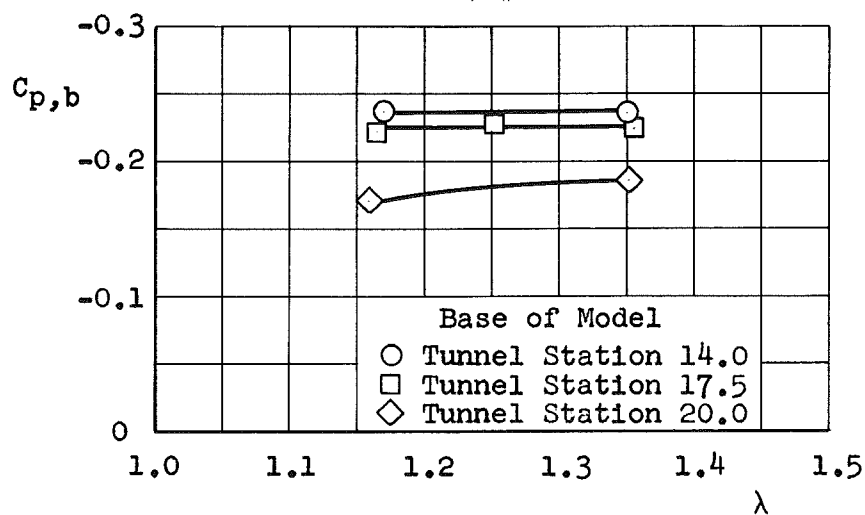
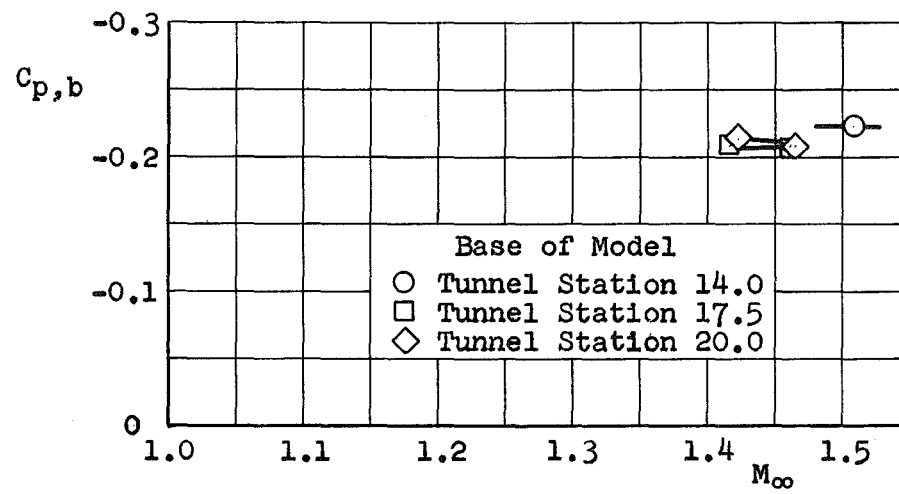
d.  $M_\infty = 1.00, \theta_w = 0$ e.  $M_\infty = 1.10, \theta_w = 0$ f.  $M_\infty = 1.20, \theta_w = -0.25$ 

Fig. 11 Continued



g.  $M_\infty = 1.60$ ,  $\theta_w = 0.30$

Fig. 11 Concluded

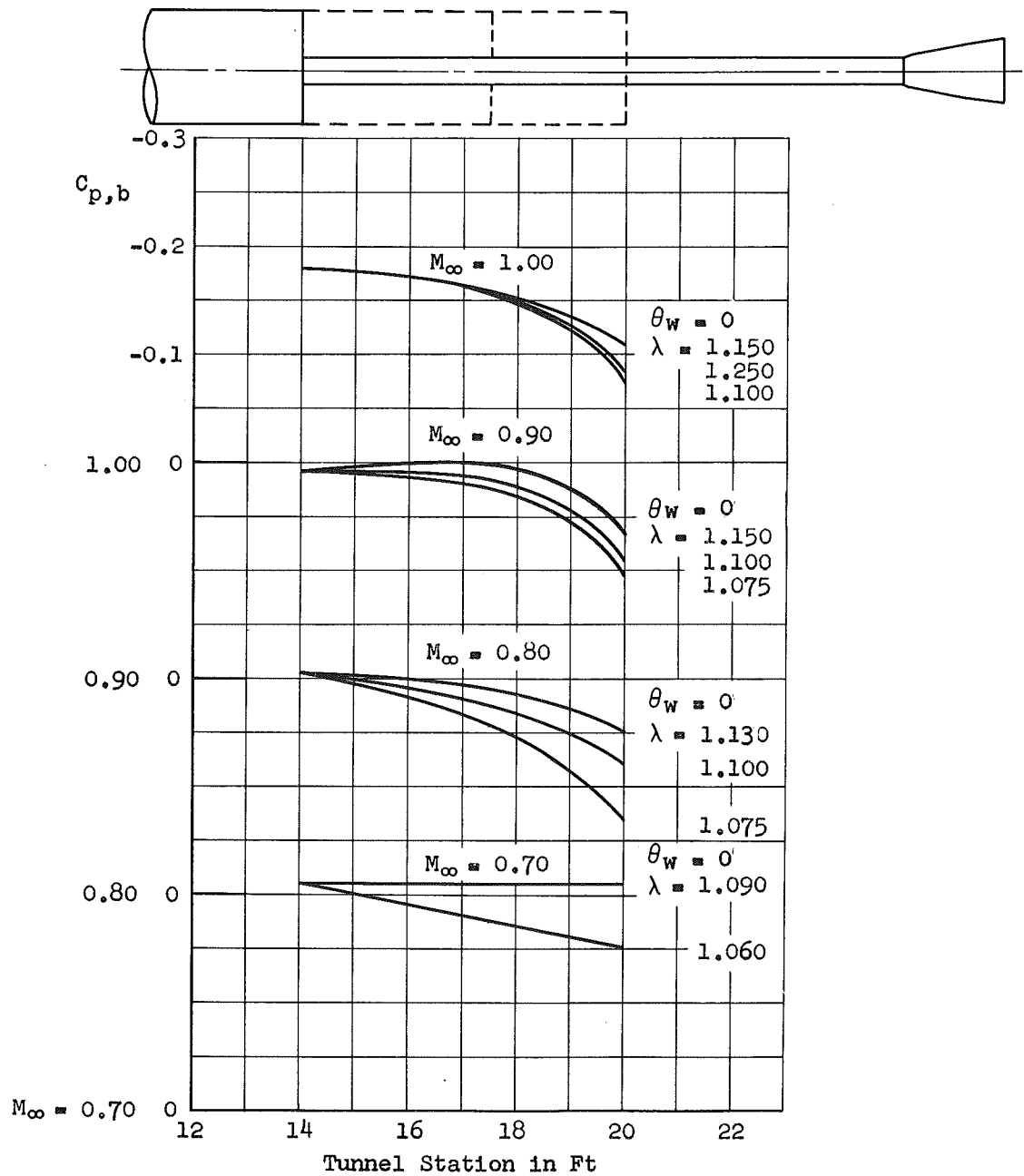


Fig. 12 Variation of Model Base Pressure Coefficients with Base Location in the Test Section for Various Values of Pressure Ratio and Mach Numbers from 0.70 to 1.60

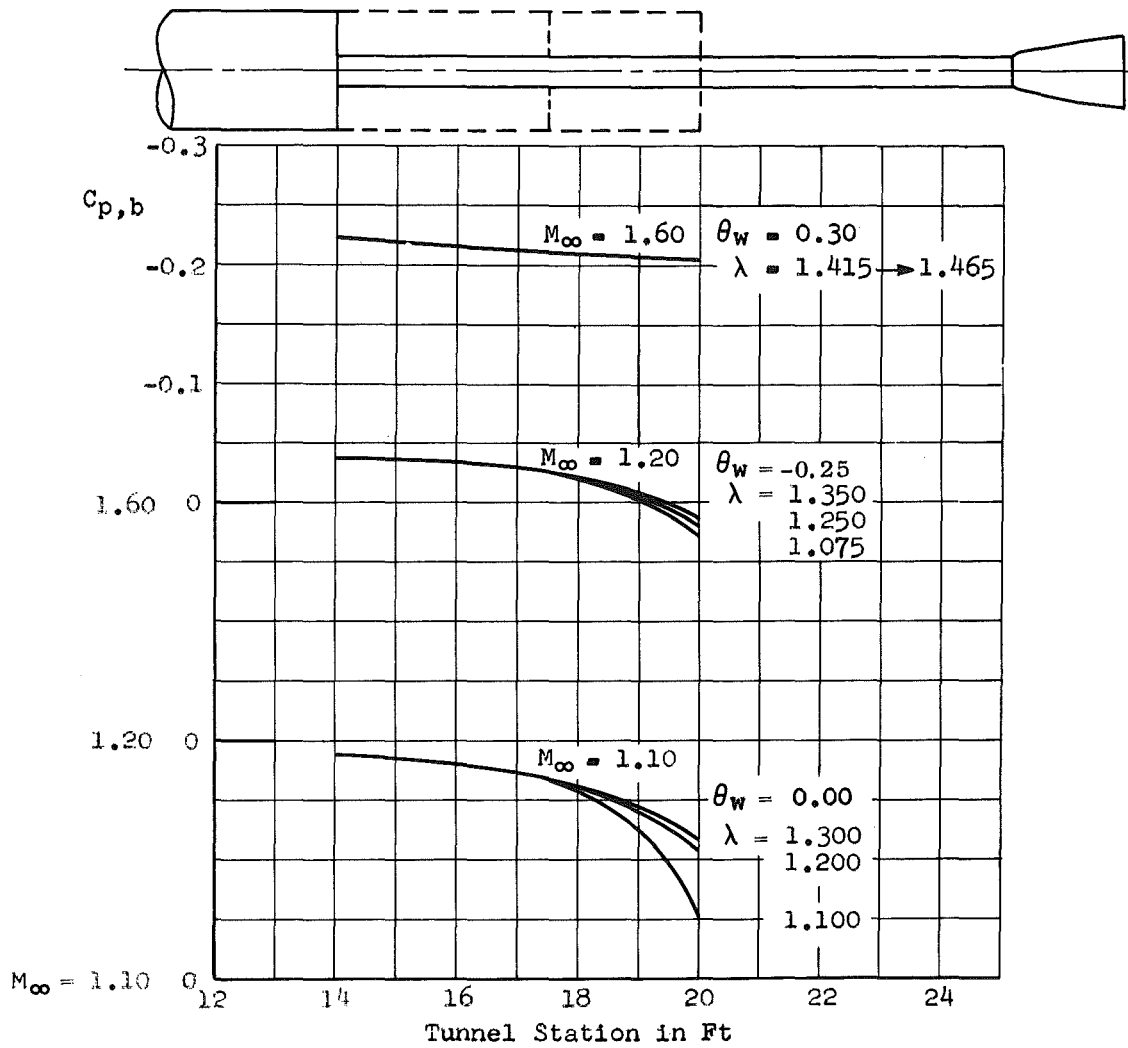


Fig. 12 Concluded